

CRS Report for Congress

Climate Change: Science and Policy Implications

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Prepared for Members and
Committees of Congress

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Climate Change: Science and Policy Implications

Summary

Almost all scientists agree that the Earth's climate is changing, having warmed by 0.6 to 0.9° Celsius (1.1 to 1.6° Fahrenheit) since the Industrial Revolution. Science indicates that the Earth's global average temperature is now approaching, or possibly has passed, the warmest experienced since human civilizations began to flourish about 12,000 years ago. During the 20th Century, some areas became wetter while others experienced more drought. Most climate scientists conclude that humans have induced a large part of the climate change since the 1970s. Although natural forces such as solar irradiance and volcanoes contribute to variability, scientists cannot explain the climate changes of the past few decades without including the effects of elevated greenhouse gas (GHG) concentrations resulting from fossil fuel use, land clearing, and industrial and agricultural emissions. Over the past 150 years, measured carbon dioxide concentrations have risen by more than one-third, from about 280 parts per million (ppm) to about 380 ppm. The United States contributes almost one-fifth of net global greenhouse gas emissions. Some impacts of climate change are expected to be beneficial (e.g., increased agricultural productivity in some regions), whereas others are expected to be adverse (e.g., drought in some regions, rising sea levels in some coastal areas).

Forecasting future climate conditions is challenging, and some major processes remain poorly understood. However, methods are improving to characterize the risks. Scientists have found it is very likely that rising greenhouse gas concentrations, if they continue unabated, will raise the global average temperature above natural variability by at least 1.5° Celsius (2.7° Fahrenheit) during the 21st Century (above 1990 temperatures), with a small likelihood that the temperature rise may exceed 5°C (9°F). The projections thought most likely by many climate modelers are for a greenhouse gas-induced temperature rise of approximately 2.5 to 3.5°C (4.5 to 6.3°F) by 2100. However, the magnitude, rapidity, and details of the change are likely to remain unclear for some time. Future climate change may advance smoothly or sporadically, with some regions experiencing more fluctuations in temperature, precipitation, and frequency or intensity of extreme events than others. Some scientists emphasize potential beneficial effects of climate change, or count on the ability of humans to adapt their behaviors and technologies to manage climate change in the future; other scientists argue that the benefits of climate change may be limited, even accounting for probable adaptation and its costs, and that there are risks of abrupt, surprising change with accompanying dislocations.

The continuing scientific process has resulted in a better understanding of climate change and generally confirms the broad conclusions made in previous decades by the preponderance of scientists: that human activities emit greenhouse gases that influence the climate, with potentially serious effects. Details have been revised or refined, but the basic conclusion of the risks persists. The principal questions remaining for the majority of scientists concern not whether greenhouse gases will result in climate change, but the magnitude, speed, geographic details, and likelihood of surprises, and the appropriate timing and options involved in addressing the human components of climate change.

Contents

Introduction	1
Changes Observed in the Earth's Climate	7
Global Climate Changes	7
Global Temperature	7
Global Precipitation	10
Climate Extremes	10
Climate Changes Observed in the United States	12
Climate Lessons from the Distant Past	15
Observed Impacts	17
Likely Causes of Global Climate Change	20
Human Activities that Influence Climate Change	22
Greenhouse Gases	22
Tropospheric Ozone	27
Sulfur and Carbon Aerosols	27
Emissions from Aviation	28
Land Surface Changes	28
Methods To Compare Human and Natural Causes	30
Attribution of Climate Change in the 20 th Century	32
Projections of Future Human-Driven Climate Change	33
Impacts of Projected Climate Change	36
Implications of Climate Change for the Federal Government	42
Implications for Policy	43
Appendix A: Natural Forces that Influence Climate	47
Earth's Orbit Around the Sun	47
Solar Activity	47
Ocean Variability	48
Volcanic Eruptions	48
Release of Methane Clathrates from Ocean Beds	49
Water Vapor	49
Chaotic Variability	50

List of Figures

Figure 1. Global Temperature Change Since the Industrial Revolution	8
Figure 2. Trends in Average Annual Temperature, 1901-2005	9
Figure 3. Changes in Frequency of Extreme Precipitation	11
Figure 4. Sectoral Shares of Global GHG Emissions in 2000	24
Figure 5. CO ₂ , Methane and Nitrous Oxide Concentrations over 400,000 Years Ago to 2004	26
Figure 6. Estimated Effects of Different Forcings on Global Temperature Since 1880	32

List of Tables

Table 1. History of U.S. Expenditures for Climate Change Science	2
Table 2. Trends in U.S. Temperature and Precipitation Change from 1902 to 2005, by Climatic Region	14

Climate Change: Science and Policy Implications

Introduction

CLIMATIC EFFECTS OF POLLUTION: Carbon dioxide is being added to the earth's atmosphere by the burning of coal, oil and natural gas at the rate of 6 billion tons a year. By the year 2000 there will be about 25% more CO₂ in our atmosphere than at present. This will modify the heat balance of the atmosphere to such an extent that marked changes in climate, not controllable through local or even national efforts, could occur. Possibilities of bringing about countervailing changes by deliberately modifying other processes that affect climate may then be very important.

President's Science Advisory Panel, 1965¹

For more than a century, scientists have known that adding carbon dioxide and certain other gases to the atmosphere could warm the Earth, as expressed in the quote above. During the past decade, mounting scientific evidence and public debate have generated interest in the U.S. Congress to understand climate change, and potentially to address related emissions of carbon dioxide, methane, and additional gases generated by human activities. These human-related emissions have accumulated in the atmosphere, raising concentrations dramatically. For example, carbon dioxide emissions associated mostly with fossil fuel combustion and land clearing have increased atmospheric concentrations by one-third since the Industrial Revolution, from about 280 parts per million (ppm) in 1850 to 380 ppm today.²

Investment in science and technological research has been the cornerstone of the federal strategy since the 1960s. Great strides have been made to collect observations of relevant Earth processes; to develop a variety of models to analyze and forecast atmospheric, ocean, land, and related economic and energy systems; and to understand the potential impacts of climate change on humans and ecosystems.

¹ President's Science Advisory Panel, *Restoring the Quality of Our Environment: Report of the Environmental Pollution Panel*, Report of The Environmental Pollution Panel, President's Science Advisory Committee, The White House (November 1965), p. 9.

² Neftel, A., H. Friedli, E. Moor, H. Löttscher, H. Oeschger, U. Siegenthaler, and B. Stauffer, 1994, *Historical CO₂ record from the Siple Station ice core*, in *Trends: A Compendium of Data on Global Change*, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy (Oak Ridge: TN). Also, World Data Centre for Greenhouse Gases (WDCGG), *WMO Greenhouse Gas Bulletin: The State of Greenhouse Gases in the Atmosphere Using Global Observations through 2005* (Geneva, 2006), at [<http://gaw.kishou.go.jp/wdcgg.html>].

Research has been conducted by universities, governmental agencies, research institutions, and the private sector.

A history of climate change science funding is provided in **Table 1**.³ Most U.S. funding has gone to researchers through the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the Department of Energy (DOE),⁴ as well as smaller amounts through other U.S. agencies and the governments of other nations. Research collaboration across countries, gaining efficiencies and insights across boundaries, has proceeded through the International Biosphere/Geosphere Program, the World Meteorological Organization (WMO), and others. The products — data, models, and analyses — have been peer-reviewed, repeated, reproduced or contradicted, debated, and updated. Dozens of assessments of various aspects of climate change science have been conducted by public multi-disciplinary bodies, including the National Academy of Science (NAS), the U.S. Congress's former Office of Technology Assessment, and the Intergovernmental Panel on Climate Change (IPCC).

Table 1. History of U.S. Expenditures for Climate Change Science
(\$ millions)

Fiscal Year	Actual \$	Constant (2005) \$
1989	134	209
1990	659	975
1991	954	1,355
1992	1,110	1,531
1993	1,326	1,775
1994	1,444	1,885
1995	1,760	2,234
1996	1,654	2,039
1997	1,656	1,995
1998	1,677	1,989
1999	1,657	1,925
2000	1,687	1,896
2001	1,728	1,886
2002	1,667	1,792
2003	1,766	1,857
2004	1,977	2,023
2005	1,865	1,865
2006 Estimate	1,709	1,674
2007 Request	1,715	1,643

Source: CCSP Annual Report to Congress, [<http://www.climatescience.gov/infosheets/highlight2/default.htm#funding>], accessed Jan. 18, 2007.

³ The science funding presented in **Table 1** is a subset of total U.S. expenditures on climate change. For more information, see CRS Report RL33817, *Climate Change: Federal Expenditures*, by Jane A. Leggett.

⁴ Funding also has been made available through the predecessors of these organizations.

The IPCC is the preeminent international body charged with periodically assessing technical knowledge of climate change. It draws on thousands of scientists with expertise on all aspects of climate change. The Fourth Assessment Report (AR4) of the IPCC assessment is being issued as several reports in 2007. A summary of selected key findings of the science assessment⁵ is provided below in “Intergovernmental Panel on Climate Change — Climate Change 2007: The Physical Science Basis.” Many governments use the IPCC assessments as one input to their policy deliberations. The U.S. government has been a primary supporter of the IPCC assessment, by sponsoring much of the research and monitoring that underpins the assessment, as well as many experts representing a broad range of views on specific topics, and by coordinating both external expert and governmental peer reviews of the reports.

The continuing scientific process has resulted in an understanding of climate change that is increasingly robust and has withstood a multitude of challenges; in most respects, the evolving science confirms the broad conclusions made in previous decades by the preponderance of scientists. Many details and complexities, however, remain nebulous. Although most scientists are confident in their current understanding of climate change, they are less certain about the future magnitude, timing, and geographic details.

Climate Change Science Is a Process

The evolution of scientific understanding of climate change is an example of the process of science. It is iterative, beginning with statements of hypotheses, followed by testing and observations, scrutiny by other scientists, reproduction or repudiation of results, and revisions to the state of knowledge. The practice of critique and revision is desirable to support continuous improvement of knowledge; some comments provide insights while others may be refuted. Research may decrease certainty, or enhance it. The objective, like most science, is to be able to produce ever more reliable predictions.

Such has been the case following the discovery described by Joseph Fourier in 1827 that Earth’s atmosphere acts like the glass of a greenhouse, letting in solar energy, then trapping some of its heat, hence influencing the temperature of the Earth’s surface. Related findings have been tested, critiqued, refuted, revised and improved over almost two centuries. As a result of the scientific process, most scientists are confident in their current understanding of climate change and the role of human activities, including emissions of so-called *greenhouse gases*. Ongoing research, debate, and refinement have yielded broadly accepted agreement on climate change science.

⁵ Intergovernmental Panel on Climate Change Working Group I, *Climate Change 2007: The Physical Basis* (Cambridge, UK: Cambridge University Press, 2007).

**Intergovernmental Panel on Climate Change
Climate Change 2007: The Physical Science Basis**

In February 2007, the Intergovernmental Panel on Climate Change (IPCC) released its fourth assessment of the science of climate change, updated with research reported over the previous six years. Selected major findings from this report include the following:

- “Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years.”
- “The atmospheric concentration of carbon dioxide in 2005 exceeds by far the natural range over the past 650,000 years (180 to 300 ppm) as determined by ice cores.”
- “The primary source of the increased atmospheric concentration of carbon dioxide since the pre-industrial period results from fossil fuel use, with land use change providing another significant but smaller contribution. Annual fossil fuel carbon dioxide emissions increased from an average of 6.4 [6.0 to 6.8] GtC per year in the 1990s, to 7.2 [6.9 to 7.5] GtC per year in 2000-2005 Carbon dioxide emissions associated with land-use change are estimated to be 1.6 GtC [0.5 to 2.7] per year over the 1990s, although these estimates have a large uncertainty.”
- “Changes in solar irradiance since 1750 are estimated to cause a radiative forcing ... which is less than half the estimate given in the TAR [Third Assessment Report, 2001, of the IPCC].”
- “Warming of the climate system is unequivocal.” The updated linear trend from 1906 to 2005 is 0.74°C [1.3°F].
- “Urban heat island effects are real but local, and have a negligible influence (less than 0.006°C [0.01°F] per decade over land and zero over the oceans).”
- “New data ... now show that losses from the ice sheets of Greenland and Antarctica have very likely contributed to sea level rise over 1993 to 2003.”
- “At continental, regional and ocean basin scales, numerous long-term changes in climate have been observed. These include changes in Arctic temperatures and ice, widespread changes in precipitation amounts, ocean salinity, wind patterns and aspects of extreme weather including droughts, heavy precipitation, heat waves and the intensity of tropical cyclones.... Some aspects of climate have not been observed to change.”

- “Paleoclimate information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1300 years. The last time the polar regions were significantly warmer than present for an extended period (about 125,000 years ago), reductions in polar ice volume led to 4 to 6 meters [13 to 20 feet] of sea level rise.”
- “Most of the observed increase in globally averaged temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations.”
- “Difficulties remain in reliably simulating and attributing observed temperature changes at smaller [than continental] scales.”
- “For the next two decades at warming of about 0.2°C [0.36°F] per decade is projected for a range of SRES emission scenarios. Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C [0.2°F] would be expected.”
- “The best estimate for the low [SRES greenhouse gas emission] scenario (B1) is 1.8°C (likely range is 1.1°C to 2.9°C) [3.2°F (likely range is 2.0°F to 5.2°F)], and the best estimate for the high scenario (A1F1) is 4.0°C (likely range is 2.4°C to 6.4°C) [5.2°F (likely range is 4.3°F to 9.5°F)].”
- “Warming is expected to be greatest over land and at most high northern latitudes, and least over the Southern Ocean and parts of the North Atlantic ocean.”
- “It is very likely that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent.”
- “Increases in the amount of precipitation are very likely in high-latitudes, while decreases are likely in most subtropical land regions (by as much as about 20% in the A1B scenario in 2100,... continuing observed patterns in recent trends.”
- “Anthropogenic warming and sea level rise would continue for centuries due to the timescales associated with climate processes and feedbacks, even if greenhouse gas concentrations were to be stabilized.”
- “Based on current understanding of climate carbon cycle feedback, model studies suggest that to stabilise at 450 ppm carbon dioxide, could require that cumulative emissions over the 21st century be reduced from an average of approximately 670 [630 to 710] GtC to approximately 490 [375 to 600] GtC.”

Climate change has become a highly debated issue in which the U.S. Congress has maintained an active and continuing interest. Congress has provided tens of billions of dollars for research and additional programs (almost \$5 billion in FY2006). It established the Global Change Research Program (USGCRP) in the Global Change Research Act of 1990 (P.L.101-606), aimed at understanding and responding to global change, and requiring a scientific assessment for the President and Congress at least every four years, as well as annual reports on activities and budget. The Senate in 1992 ratified the Framework Convention on Climate Change, which contains commitments from the United States and other parties to improve the science and cooperate internationally on it, as well as to communicate about climate change to the public.

The first and only national assessment was released by the executive branch in 2000.⁶ *Our Changing Planet*, an annual report to Congress, outlines climate-related research progress and strategies.⁷ Various committees have held hearings to oversee existing programs and to consider further options. There has been general consensus regarding the benefits of additional scientific and technological research; however, long-standing debate exists about whether and how to attempt to achieve mitigation or adaptation through federal legislative action. As additional action is considered, an understanding of climate change science may help inform consideration of relative priorities, the scope of action, and timing, among other issues.

This report presents an overview of the science of climate change and its potential impacts. It provides highlights on the impacts of climate change itself; it does not address the mitigation of climate change (e.g., by controlling greenhouse gas emissions) nor the economic issues associated with it. This report is organized into four topics:

- Climate change and impacts that have been observed.
- Forces that are understood to be causing recent climate change.
- Projections of future climate change and impacts.
- Implications of climate change science for policy.

This report represents a snapshot of the science of climate change, which will continue to evolve. It will be updated periodically to reflect new peer-reviewed evidence and the developing state of scientific understanding.

⁶ U.S. Global Change Research Program, *U.S. National Assessment of the Potential Consequences of Climate Variability and Change: A detailed overview of the consequences of climate change and mechanisms for adaptation* (Washington, 2000), available at [<http://www.usgcrp.gov/usgcrp/nacc/default.htm>].

⁷ U.S. Climate Change Science Program Office, *Our Changing Planet: The U.S. Climate Change Science Program for Fiscal Year 2007: A Report by the Climate Change Science Program and The Subcommittee on Global Change Research, A Supplement to the President's Fiscal Year 2007 Budget* (Washington, 2006), at [<http://www.usgcrp.gov/usgcrp/Library/ocp2007/default.htm>].

Changes Observed in the Earth's Climate

Scientists agree that the Earth's climate is changing. The average global surface temperature has increased since the Industrial Revolution, by about 0.6 to 0.9° Celsius (1.1 to 1.6° Fahrenheit) from 1880 to today. The U.S. temperature has risen at roughly twice the global average rate since the 1970s. The global climate of the past few decades is likely approaching, or has already passed, the warmest since the rise of human civilizations around 12,000 years ago.⁸ Precipitation in the 20th Century has increased by about 2%, more in the high northern latitudes, while drying has occurred in parts of the tropics, especially in the Sahel and southern Africa. Extreme precipitation events have increased in most of the few locations where data are adequate for analysis.

The following sections cover *observed* climate change. The initial section describes changes in the climate measured around the globe, first in temperature, then precipitation, then extreme events. The subsequent section describes climate changes specific to the United States. The last section on observed climate change identifies findings from the study of climate centuries to millenia ago that have relevance to consideration of recent and potential future climate change.

Global Climate Changes

Global Temperature. The average temperature of the Earth's surface, the *global mean temperature* (GMT), has increased about 0.6 to 0.9°C (about 1.1 to 1.6°F) from 1880 to 2004 (**Figure 1**).⁹ Warming occurs over land¹⁰ and sea surfaces.¹¹ The warming during the 20th century, however, was not smooth. Global warming occurred from around 1910 to 1945, followed by a period of slightly declining or stable temperatures into the 1970s. Since 1979, warming has returned to about twice the rate of the 20th Century average, at about 0.18°C per decade

⁸ Obasi, Godwin O.P., "Climate Change — Reality, Expectation, and the Role of WMO and National Meteorological and Hydrological Services," lecture presented at the Sixth Technical Conference on Management for Development of Meteorological Services in Africa (Abuja, Federal Republic of Nigeria), November 6, 2000. Also, Hansen, J., et al., "Global temperature change," *PNAS*, 103 (2006), pp. 14288-14293.

⁹ Lower value provided by National Oceanic and Atmospheric Administration/National Climate Data Center (NOAA/NCDC), *Climate of 2005 — Annual Report*, NASA Goddard Institute for Space Studies (2006). The upper value comes from Intergovernmental Panel on Climate Change Working Group I, *Climate Change 2007: The Physical Basis* (Cambridge, UK: Cambridge University Press, 2007).

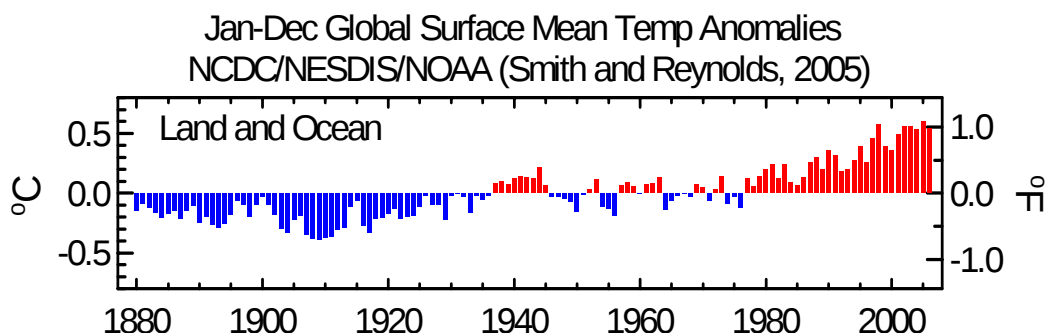
¹⁰ Adjustments to the measurements to account for urban heat islands, relocation of observation stations, changes in measurement techniques, etc. are described by NOAA/NCDC at [<http://www.ncdc.noaa.gov/oa/climate/research/ushcn/ushcn.html>], which also provides detailed technical references.

¹¹ T.M. Smith and R.W. Reynolds, "A global merged land air and sea surface temperature reconstruction based on historical observations (1880-1997)," *J. Clim.*, vol. 18 (2005), pp. 2021-2036. The fact that warming occurs in sea surface temperatures is evidence that the observed global warming is not an artifact of placement of weather stations and urbanization.

(0.32°F/decade). A panel of the National Academy of Science has reconciled earlier disagreement in confirming that warming has occurred also in the mid-troposphere,¹² though less than at the surface.¹³

Globally, 2005 was the warmest in nearly 130 years of direct measurements; 2006 was the sixth warmest year on record. The 10 warmest years on record have occurred since 1994.

Figure 1. Global Temperature Change Since the Industrial Revolution



Source: National Oceanic and Atmospheric Administration, National Climatic Data Center.

Note: Temperature anomalies are the differences between each year's temperature and the climate normal for 1961 to 1990, represented by the horizontal line at 0.0, which is from the University of East Anglia's Climate Research Unit.

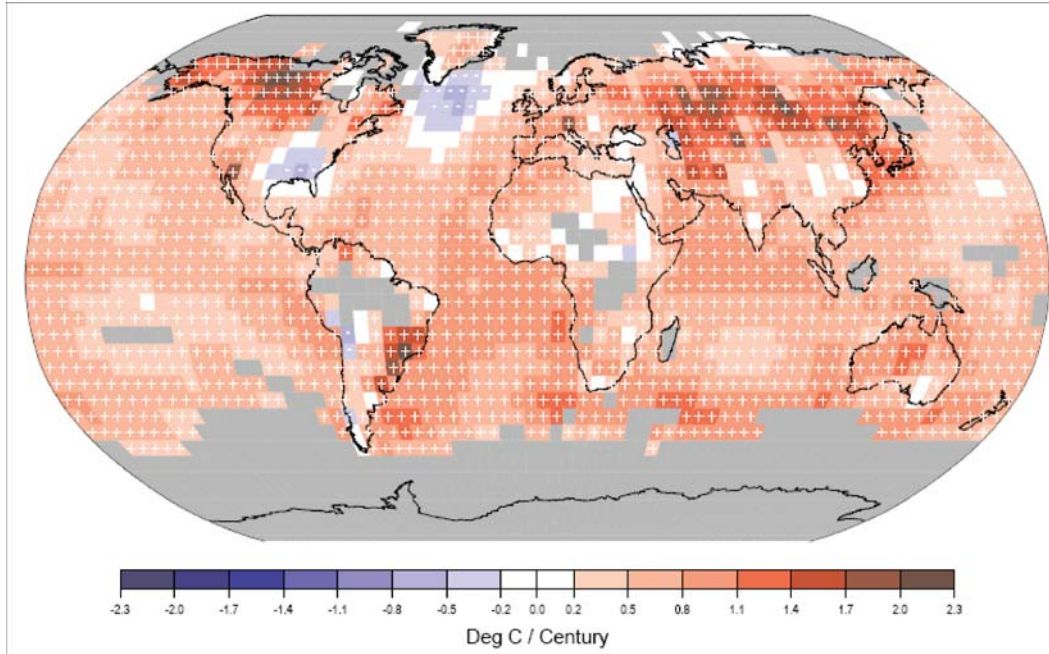
¹² The *troposphere* is the portion of the atmosphere that extends from the Earth's surface up to the *stratosphere*, about 17 kilometers high near the Equator and about 7 kilometers high near the Poles.

¹³ National Research Council, *Reconciling Observations of Global Temperature Change*, National Academy Press (Washington, 2000):

In the opinion of the panel, the warming trend in global-mean surface temperature observations during the past 20 years is undoubtedly real and is substantially greater than the average rate of warming during the twentieth century. The disparity between surface and upper air trends in no way invalidates the conclusion that surface temperature has been rising.... [T]he troposphere actually may have warmed much less rapidly than the surface from 1979 into the late 1990s, due both to natural causes (e.g., the sequence of volcanic eruptions that occurred within this particular 20-year period) and human activities (e.g., the cooling of the upper part of the troposphere resulting from ozone depletion in the stratosphere). (p.2)

As **Figure 2** shows, surface temperatures have increased nearly everywhere, except for cooling in parts of the North Atlantic. Warming has been greatest in the northern high latitudes, such as Alaska, Canada, Northern Europe, and Russia.¹⁴ Although warming over most land areas has occurred year-round, the increases have generally been greater in the Northern Hemisphere during winter and spring.

Figure 2. Trends in Average Annual Temperature, 1901-2005



Source: NOAA/NCDC, Global Historical Climatology Network (GHCN)-Extended Reconstructed Sea Surface Temperature (ERSST) data set.

Notes: Cells for which the temperature trend is statistically significant are marked with a + sign if positive, and - if negative. Data for cells without a + or - mark do not exhibit a statistically significant trend for the 20th century. Significant cooling has occurred only in the northern Atlantic surface, the southeast United States, and the southwest of South America.

¹⁴ Temperatures higher than today occurred from about 1925 to 1965, in the northern high latitudes (60°N and above). Thomas L. Delworth and T.R. Knutson, "Simulation of Early 20th Century Global Warming," *Science*, 287, no. 2246 (2000). The rapid Arctic warming concentrated around 1940 was not widespread across all latitudes, whereas warming since the 1980s can be seen at all latitudes.

Strong evidence of global warming since 1955 comes from measurements of heat content of the world's upper oceans, overall by 0.04°C since 1955.¹⁵ Because oceans store about 84% of the heat on Earth,¹⁶ this small warming is considered a strong signal of long-term change. Additional evidence of global warming comes from the detection of increasing continental temperatures (measured by boreholes into rock below the surface), by about 0.02°C, during the past five decades.¹⁷ Both ocean and continental warming corroborate the elevated surface air temperatures.

Global Precipitation. Humans and ecosystems are affected by many aspects of climate, including precipitation, which has increased over the past century. This observed increase is consistent with scientific understanding that as warming temperatures increase evaporation, precipitation will increase to maintain balance in the water cycle. Over land, precipitation has increased by about 2% since 1900, but the patterns are highly variable across time and in different locations. Only a few regions show significant changes (**Figure 3**). Most of the United States and other high latitudes, except eastern Russia, have seen greater wetness, whereas precipitation has decreased in the sub-tropics, such as the Sahel in Africa.

Climate Extremes. Few patterns of change have emerged globally in the frequency or intensity of most types of extreme events, according to NOAA's National Climatic Data Center (NCDC).¹⁸ No trend in global thunderstorm frequencies has been identified. Though there has been a clear trend toward less frequent extremely cold winter temperatures in some locations, there is no trend in the frequency of extremely high temperatures. Researchers at NOAA's National Center for Atmospheric Research (NCAR) have found that "[w]idespread drying occurred over much of Europe and Asia, Canada, western and southern Africa, and eastern Australia. Rising global temperatures appear to be a major factor."¹⁹ Drought area increased more than 50%, mostly due to conditions in the Sahel and southern Africa over the past few decades. Researchers have found that *great floods*²⁰ worldwide increased significantly during the 20th Century, especially in the latter half of the period. The frequency of floods exceeding the 200-year flood levels also

¹⁵ Sydney Levitus et al., "Warming of the World Ocean, 1955-2003," *Geophysical Research Letters*, 32, no. 02604 (2005). "[A] mean temperature change of 0.01°C of the world ocean would correspond roughly to a mean temperature change of 10°C of the global atmosphere if all the heat associated with this ocean anomaly was instantaneously transferred from the ocean to the atmosphere." See also Sydney Levitus et al., "Anthropogenic Warming of Earth's Climate System," *Science*, 292, no. 5515 (April 13, 2006), pp. 267-270.

¹⁶ Levitus et al. 2005. About 84% of the Sun's energy absorbed by the Earth since the 1950s has been stored in the oceans.

¹⁷ Ibid.

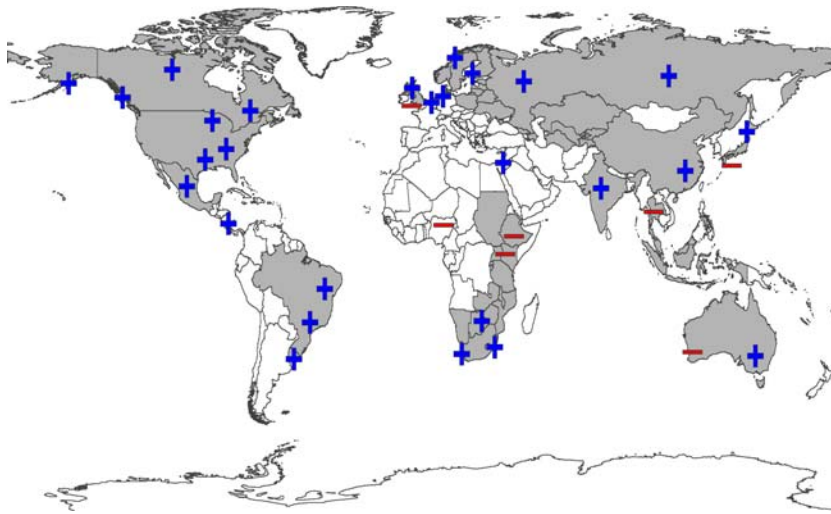
¹⁸ See [<http://www.ncdc.noaa.gov/oa/climate/globalwarming.html#Q3>].

¹⁹ Dai, A., K. E. Trenberth, and T. Qian, "A global data set of Palmer Drought Severity Index for 1870-2002: Relationship with soil moisture and effects of surface warming," *Hydrometeorology*, 5 (2004), pp. 1117-1130. See also [<http://www.cgd.ucar.edu/cas/catalog/climind/pdsi.html>] and [http://www.ucar.edu/news/releases/2005/drought_research.shtml].

²⁰ *Great floods* are defined as exceeding the levels of floods that would occur on average once in every 100 years — *the 100-year flood* — in basins larger than 200,000 km².

increased significantly, while the frequency of floods having return periods shorter than 100 years did not increase significantly.²¹ In most regions, insufficient data remain a challenge for assessing trends in climate variability, because of the infrequency of events (by definition) and their spatial variability. In **Figure 3**, countries that are not shaded do not have sufficient data to analyze rates of heavy precipitation. Figure 3 shows that most often, in regions that have robust precipitation data, extreme precipitation has increased; in a few regions, such as the Sahel and East Africa, extreme precipitation has decreased.

Figure 3. Changes in Frequency of Extreme Precipitation



Source: D.R. Easterling et al., “Observed Variability and Trends in Extreme Climate Events: A Brief Review,” *Bulletin of the American Meteorological Society*, 81 (March 2000), pp. 417-425. Available at [<http://www.ncdc.noaa.gov/oa/pub/data/special/extr-bams2.pdf>]. Figure provided by NOAA National Climate Data Center.

Notes: Signs on the map indicate regions where significant changes in heavy precipitation have occurred during the past decades, where sufficient data are available to analyze the trend. Plus signs indicate positive trends in heavy precipitation; negative signs indicate decreasing trends in heavy precipitation. Locations that are not shaded do not have sufficient data to analyze trends.

²¹ P.C.D. Milly et al., “Increasing risk of great floods in a changing climate,” *Nature*, 415 (January 31, 2002), pp. 514-517.

Contentious debate continues regarding trends in hurricane or cyclone frequency and intensity. For about 85% of the world's oceans, data are inadequate to detect long-term changes.²² Only in the extra-tropical²³ Atlantic basin has research established a positive relationship between sea surface temperatures and increased number and severity of hurricanes or cyclones.²⁴ Since the mid-1980s, satellite data reveal a distinct increase in tropical cyclone activity associated with higher eastern Atlantic sea surface temperatures, as well as other factors.²⁵ Much longer series of high-quality observations and improved understanding of tropical cyclones are needed to provide definitive attribution of changes in hurricane activity to natural variability, greenhouse gas (GHG) forcing, or other processes. A November 2006 meeting of international experts on tropical cyclones, convened by the World Meteorological Organization, concluded that “[d]espite the diversity of research opinions on this issue, it is agreed that if there has been a recent increase in tropical cyclone activity that is largely anthropogenic in origin, then humanity is faced with a substantial and unanticipated threat.”²⁶

Climate Changes Observed in the United States

At the global scale, average annual temperature and precipitation have increased over the past century, especially since the 1970s. At a regional scale, such as for the United States, significant climate changes have also been measured.

In the United States, both temperatures and precipitation have increased during the 20th Century (**Table 2**), but with important regional variations.²⁷ The mean temperature for the contiguous United States has increased by 0.6°C (1.1°F) since 1901 (0.06°C or 0.1°F per decade), generally following the global oscillations. From

²² Landsea, C.W., G.D. Bell, W.M. Gray, S.B. Goldenberg, “The extremely active 1995 Atlantic hurricane season: Environmental conditions and verification of seasonal forecasts,” *Mon. Wea. Rev.*, 126 (1998), pp. 1174-1193; Landsea, C. W., “2005: Hurricanes and global warming,” *Nature*, 438, doi:10.1038/nature04477; Landsea, C.W., B.A. Harper, K. Hoarau, and J.A. Knaff, “Can we detect trends in extreme tropical cyclones?” *Science*, 313 (2006), pp. 452-454.

²³ *Extra-tropical* means outside of the tropics.

²⁴ World Meteorological Organization, “*Statement on Tropical Cyclones and Climate Change*” *Report of the International Workshop on Tropical Cyclones* IWTC-6, November 2006.

²⁵ Kerry Emanuel, “Increasing destructiveness of tropical cyclones over the past 30 years,” *Nature*, 436 (August 4, 2005); P.J. Webster et al., “Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment,” *Science*, 309, no. 5742 (September 16, 2005), pp. 1844-1846; Stanley B. Goldenberg et al., “The Recent Increase in Atlantic Hurricane Activity: Causes and Implications,” *Science*, 293, no. 5529 (July 20, 2001), pp. 474-479.

²⁶ World Meteorological Organization. *Ibid.*

²⁷ NOAA/National Climate Data Center, NOAA/NCDC. 2006, *Global Surface Temperature Anomalies*, [<http://www.ncdc.noaa.gov/oa/climate/research/anomalies/anomalies.html>] (accessed January 19, 2007). Described in Smith, T. M., and R. W. Reynolds, “A global merged land air and sea surface temperature reconstruction based on historical observations (1880-1997),” *J. Clim.*, 18 (2005), pp. 2021-2036.

1979 to 2003, the rate of warming in the United States, at 0.33°C (0.6°F) per decade, has been about twice the rate of the global average. Two regional exceptions to this overall warming were (1) cooler winters and springs in the Southeast from 1901 to 1978, which reversed to warming after 1979 (except in Florida), and (2) generally stable or cooler summer and autumn months in the South and central United States. The warmest year for the United States in the 20th Century was 1998 (with temperatures boosted by El Nino²⁸), followed by 1934; 2006 was the third-warmest year in the U.S. record, about 1.1°C (2°F) above the 20th Century average.²⁹

U.S. average precipitation has increased 6.1% since 1895, but with more variability and a less distinct pattern than temperature (**Table 2**). The increase in precipitation was particularly pronounced in the central, south, and east north-central climatic regions. The Northwest has had large and increasing inter-annual cycles of precipitation since the 1970s, associated with ENSO (El Nino-Southern Oscillation) events. In contrast, the Southwest and Hawaii have had decreases in precipitation, although the trends are not statistically significant because of high inter-annual variability. The 20th Century was also marked by strong and extensive droughts in 1931 to 1938 and 1951 to 1956 in the United States.³⁰

²⁸ The *El Nino-Southern Oscillation* (El Nino, or ENSO) is an irregularly occurring climate event (typically lasting one to two years every two to seven years) associated with above-normal sea surface temperatures in the central tropical Pacific Ocean, as well as the Atlantic and Indian Oceans; it affects weather across the globe. Conversely, La Nina is associated with lower than normal sea surface temperatures.

²⁹ NOAA/National Climate Data Center, NOAA/NCDC, 2006, Global Surface Temperature Anomalies, [<http://www.ncdc.noaa.gov/oa/climate/research/anomalies/anomalies.html>] (accessed January 19, 2007). Described in Smith, T. M., and R. W. Reynolds, "A global merged land air and sea surface temperature reconstruction based on historical observations (1880-1997)," *J. Clim.*, 18 (2005), pp. 2021-2036.

³⁰ However, the droughts in the 1930s and 1950s were neither more intense nor as sustained as droughts that are apparent in the geologic record of the past 1,000 years. Evidence suggests that two droughts lasting more than 20 years in much of the United States occurred in the late 13th and 16th Centuries, and that some droughts in the Sierra Nevada may have lasted more than 100 years before 1350 and 1110 A.D. Peter B. deMenocal, "Cultural Responses to Climate Change During the Late Holocene," *Science*, 292 (April 27, 2001), pp. 667-674.

Table 2. Trends in U.S. Temperature and Precipitation Change from 1902 to 2005, by Climatic Region

Climatic Region	Temperature (degrees F)	Precipitation (%)
Northeast	1.69	7.31
Southeast	-0.04	2.96
Central	0.16	7.91
South	0.04	11.08
East North Central	1.60	11.55
West North Central	1.70	2.96
Southwest	1.63	1.47
West	2.07	8.96
Northwest	1.70	5.45
Alaska	3.31	6.08
Hawaii	1.18	-9.25

U.S. Climatic Regions



Source: Data and figure provided by NOAA/National Climate Data Center, at [<http://www.ncdc.noaa.gov/oa/ncdc.html>].

Notes: The U.S. map is also available in color at [http://www.epa.gov/climatechange/science/recentpsc_precipanom.html]; the shading of each grid cell shows the trend of annual average precipitation for that cell during the period 1895 to 2003. The trends, both in the table and the map, are determined by statistical regression analysis.

The frequency of extreme precipitation events in the United States has increased since the 1920s and 1930s, although frequencies in the late 1800s and early 1900s were about as high as in the 1980s and 1990s.³¹ The number of events “much above normal” has increased by 20% since 1910.³² Extreme precipitation events lasting from one to seven days increased at a rate of about 3% per decade from 1931 to 1996.³³ In the Southeast, very heavy precipitation not associated with hurricanes has increased by about 2.6% per decade on average in the 20th Century.³⁴ Although such increases in precipitation intensity and duration tend to increase the risk of flooding, some land uses and investments in flood management actively work to reduce such risks. Tornado frequency since 1955 has not changed much, although the record is complicated by reporting uncertainties.³⁵

Climate Lessons from the Distant Past

Climate change since the Industrial Revolution has been measured both globally and across the United States, as increases in temperature and changes in precipitation. Whether this constitutes natural variability, and how to interpret the observed change, can be informed by putting it in the context of climate changes that have occurred over the past thousand, ten thousand and hundreds of thousands of years.

A number of lessons can be gleaned from *paleoclimatology*, the study of past climates, by piecing together extensive and disparate sets of *proxy* indicators, such as ice cores, tree rings, fossil records, and the chemical composition of shells. First, modern human civilizations have developed and thrived in the stable and relatively temperate climate of the past 12,000 years, a period called the *Holocene period*. Global average temperatures have varied fairly narrowly during the past 10,000 years, within about 2°C, with the maxima around the current global mean temperature and the minimum temperatures occurring in the 16th and 17th centuries, during the Little Ice Age, about 1°C cooler than current temperatures. According to NOAA, no evidence demonstrates that global annual temperatures at any time during the Holocene were warmer than today.³⁶

³¹ Kenneth E. Kunkel, “North American Trends in Extreme Precipitation,” *Natural Hazards*, 29, no. 2 (June 2003), pp. 291-305.

³² Karl, T. R., and R. W. Knight, “Secular Trends of Precipitation Amount, Frequency, and Intensity in the United States,” *Bulletin of the American Meteorological Society*, vol. 79, no. 2 (1998), pp. 231-242.

³³ Kunkel, Kenneth E., D.R. Easterling, Kelly Redmond, and Kenneth Hubbard, “Temporal Variations of Extreme Precipitation Events in the United States: 1895-2000,” *Geophysical Research Letters*, 30, no. 17 (September 2003), pp. 1900-1903.

³⁴ Groisman, P. Y., R. W. Knight, T. R. Karl, D. R. Easterling, B. Sun, and J. H. Lawrimore, “Contemporary Changes of the Hydrological Cycle over the Contiguous United States: Trends Derived from In Situ Measurements,” *Journal of Hydrometeorology*, 5 (2004), pp. 64-85.

³⁵ NOAA/NCDC at [<http://www.ncdc.noaa.gov/oa/climate/severeweather/tornadoes.html>].

³⁶ See [<http://www.ncdc.noaa.gov/paleo/globalwarming/holocene.html>]. About 6,000 years (continued...)

Second, some climate shifts can be rapid, occurring on time scales of only years to decades. Paleoclimatological records show abrupt shifts that have included changes in hurricane frequency, flooding, drying of lakes, and several *mega-droughts* lasting decades to centuries. Recently, evidence shows that the main warming events ending the last ice age (about 15,000 years ago) took place in less than a decade. Regionally, the shift was rapid and extreme, with Greenland's temperature rising in one step of around 8°C in a decade or less.³⁷

This revelation that the Earth's climate can change abruptly, with triggers, amplifiers, and bounds that are not well understood, has precipitated grave concern among many scientists. A number of studies have found that major ecological restructuring has accompanied major climatic shifts in the past. Although human societies have proven adaptable to moderate inter-annual variability and smooth change, research in several regions indicates that significant structural, and sometimes catastrophic, reorganizations of regional civilizations (e.g., the Mayas in the 9th Century, African civilizations)³⁸ have been triggered by past significant climate changes.

³⁶ (...continued)

ago, during the so-called *Holocene Optimum*, summers (only) were warmer in the Northern Hemisphere (only) due to a shift in the Earth's orbit. The *astronomical forcing* prompting this isolated warmth has not been present during the 20th Century. A panel of the National Academy of Sciences concluded with high confidence that

global mean surface temperature was higher during the last few decades of the 20th century than during any comparable period during the preceding four centuries.... Less confidence can be placed in large-scale surface temperature reconstructions for the period from A.D. 900 to 1600. Presently available proxy evidence indicates that temperatures at many, but not all, individual locations were higher during the past 25 years than during any period of comparable length since A.D. 900. Very little confidence can be assigned to statements concerning the hemispheric mean or global mean surface temperature prior to about A.D. 900.

(National Research Council, *Surface Temperature Reconstructions for the Last 2,000 Years*, Washington: National Academies Press, 2006, p. 3).

With caution regarding the challenges and uncertainties associated with reconstructions of climates in the distant past, several researchers using independent methods (but often the same proxy data sets) have concluded that the Earth's temperature since around 1990 appears to be higher than in at least 2,000 years, above the natural variability present in the record. Further, the climate record shows that the warming over the 20th Century has occurred at a rate that is unprecedented for at least the last 1,000 years.

³⁷ National Research Council, *Abrupt Climate Change: Inevitable Surprises* (Washington: National Academies Press, 2002).

³⁸ Lonnie G. Thompson et al., "Abrupt tropical climate change: Past and present," *PNAS*, 103, no. 28 (July 11, 2006), pp. 10536-10543; R.B. Alley et al., "Abrupt Climate Change," *Science*, 299 (March 28, 2003), pp. 2005-2010; deMenocal, Peter B., "Cultural Responses to Climate Change During the Late Holocene," *Science*, 292 (2001), pp. 667-674.

Observed Impacts

Scientific research has revealed a number of changes in the Earth's climate system in the past century. This section addresses changes observed in human and ecological systems that may be associated with, and perhaps caused by, the observed climate changes.

Impacts of climate change over the past few decades are visible on human activities and ecosystems. There is a likely bias that favors the reporting of detected changes, rather than the reporting of no changes. Nonetheless, observations confirm that most biological and physical systems studied are responding to warming and other climate changes over the 20th Century in ways scientists would expect, but there have also been some surprises.

The northern boundary of successful corn production in the United States has migrated north by 100 miles over the past three decades, according to an official of the DuPont Corporation.³⁹ One study explained roughly 25% of corn and 32% of soybean yield trends in certain counties in the Midwest and Northern Great Plains by observed temperature trends from 1982 to 1998.⁴⁰ Some salmon fisheries in parts of Alaska have seen record catches, benefitting from warmer temperatures, while in western Alaska, the Pacific Northwest and Canada, salmon stocks have decreased, having passed the upper limits of their temperature tolerance, according to the Alaska Regional Assessment Group for the U.S. Global Change Research Program.⁴¹

In the U.S. West, decreasing trends in mountain snowpack and earlier snowmelt have altered the timing of stream flows.⁴² This has significant implications for flood control, irrigation and summer drying of vegetation.

Studies continue to conclude that higher temperatures increase the risks of heat-related illnesses and deaths, that these vary by location, and that the risks are elevated in some regions, older and younger age categories, and impoverished

³⁹ William Neibur, Vice President, DuPont Crop Genetics Research and Development, personal communication (October 31, 2006).

⁴⁰ David B. Lobell and Gregory P. Asner, "Climate and Management Contributions to Recent Trends in U.S. Agricultural Yields," *Science*, 299 (February 14, 2003), p. 1032.

⁴¹ Center for Global Change and Arctic System Research, *The Potential Consequences of Climate Variability and Change: Current Stresses and Future Climate Impacts on Key Economic Sectors* (December 1999), available at [<http://www.besis.uaf.edu/regional-report/Stresses1.pdf>]

⁴² McCabe, Gregory, and Martyn Clark, "Trends and Variability in Snowmelt Runoff in the Western United States," *Journal of Hydrometeorology*, 6 (2005), pp. 476-482; Mote, P.W. 2003 "Trends in Snow Water Equivalent in the Pacific Northwest and their Climatic Causes," *Geophysical Research Letters*, vol. 30, no. 12, p. 1601; Hamlet, Alan F., P.W. Mote, and D.P. Lettenmaier, "Implications of changing 20th century precipitation variability for water management in the western U.S." (2007) (forthcoming).

populations.⁴³ In Europe during the summer of 2003, as many as 52,000 people died prematurely in the most severe heat wave in at least 500 years. One study concluded it was very likely that human-driven climate change had more than doubled the risk of occurrence of such an extreme heat event.⁴⁴ Significant preparedness and emergency response systems in a number of cities have substantially lowered the local risks of mortality during heat waves over the past two decades.

Significant impacts of the warming climate are reported in ecological systems on every continent. Of more than 1,600 species analyzed by two researchers, more than half show changes in their *phenologies*, the timing of their life events (such as egg-laying or blossoming dates), or their *distributions* (where they are found), systematically and dominantly in the direction expected from regional climate changes.⁴⁵ Through the 1990s, oceanic plankton productivity has varied with sea surface temperatures, with warming significantly lowering productivity.⁴⁶ This raises concerns among scientists because plankton are a major food source for many marine species.

Coral bleaching, triggered by some heat episodes, has become increasingly widespread in many reef regions, including Hawaii, the Caribbean, and Australia's Great Barrier Reef. In addition, elevated concentrations of carbon dioxide in the atmosphere are absorbed by, and are acidifying, the world's oceans, posing risks to shell-forming organisms and marine food chains.⁴⁷

Warming and drying in southeast Alaska and the western United States from the late 1980s to the present have resulted in pest outbreaks and fires, destroying property, increasing fire management costs and loss of life, reducing economic forest

⁴³ Kristie L. Ebi et al., "Climate Change and Human Health Impacts in the United States: An Update on the Results of the U.S. National Assessment," *Environmental Health Perspectives*, 114, no. 9 (September 2006), pp. 1318-1324.

⁴⁴ Peter A. Stott, D.A. Stone, and Myles R. Allen, "Human contribution to the European heatwave of 2003," *Nature*, 432 (December 2, 2004), pp. 610-614.

⁴⁵ Camille Parmesan and Gary Yohe, "A globally coherent fingerprint of climate change impacts across natural systems," *Nature*, 421 (2003), pp. 37-42;

⁴⁶ Michael J. Behrenfeld et al., "Climate-driven trends in contemporary ocean productivity," *Nature*, 444 (December 7, 2006), pp. 752-756.

⁴⁷ Kleypas, J.A., R.A. Feely, V.J. Fabry, C. Langdon, C.L. Sabine, L.L. Robbins, et al. *Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research*, a report of a workshop held April 18-20 2006, St. Petersburg FL, [http://www.ucar.edu/communications/Final_acidification.pdf]; Orr, James C., Victoria J. Fabry, Olivier Aumont, Laurent Bopp, Scott C. Doney, Richard A. Feely, et al. "Anthropogenic Ocean Acidification over the Twenty-First Century and its Impact on Calcifying Organisms," *Nature*, 437 (September 29, 2005), pp. 681-686; Park, Geun-Ha, Kitack Lee, Pavel Tishchenko, Dong-Ha Min, Mark J. Warner, Lynne D. Talley, et al. "Large accumulation of anthropogenic CO₂ in the East (Japan) Sea and its significant impact on carbonate chemistry," *Global Biogeochemical Cycles*, 20, no. GB4013 (November 22, 2006).

production, and emitting severe air pollution with consequent health impacts.⁴⁸ Record high temperatures and droughts have also triggered extensive fires in Argentina, Greece, South Africa, and other locations. Some species, populations, and individuals have shown benefits from warming conditions, whereas others that are more reliant on cool habitats have been adversely affected or lost competitiveness.

Mountain glaciers have contracted worldwide over at least the past 200 years, with evidence that the rate of melting or flow has accelerated in recent decades, including in Argentina, Bhutan, Canada, India, Kyrgystan, Nepal, Switzerland, Tanzania, Uganda, Venezuela, and the United States. The glacial ice sheets of Greenland are melting overall, with an apparent acceleration in the period 2003 to 2005.⁴⁹ In western Antarctica, accelerated ice melting and loss contrasts with accumulating ice in East Antarctica because of increased precipitation.⁵⁰ With loss of buttressing sea ice, glacial flows have sped up in the past decade in parts of western Antarctica.⁵¹ Record low Arctic sea ice extent in 2005, at 5.6 million square kilometers, was 20% less than the 1970 to 2000 median.⁵² Polar bears, which rely on sea ice to access food, have experienced a significant decrease in cub survival rates from 2001 to 2006 in the Beaufort Sea area.⁵³ Rising absolute sea levels

⁴⁸ Breshears, David D., Neil S. Cobb, Paul M. Rich, Kevin P. Price, Craig D. Allen, Randy G. Balice, et al. "Regional vegetation die-off in response to global-change-type drought," PNAS (October 2005); Center for Global Change and Arctic System Research, *A Report of the Alaska Regional Assessment Group: Current Stresses and Future Climate Impacts on Key Economic Sectors*, Fairbanks, Alaska, 1999. Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam, "Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity," *Science*, 313 (August 18, 2006), pp. 940-943.

⁴⁹ S.B. Luthcke et al., "Recent Greenland Ice Mass Loss by Drainage System from Satellite Gravity Observations," *Science*, 314, no. 5803 (November 24, 2006), pp. 1286-1289; Luthcke et al., at [<http://cires.colorado.edu/science/groups/steffen/greenland/melt2005>]; W. Krabill et al., *Geophys. Res. Lett.*, 31, L24402 (2004); H. J. Zwally et al., *J. Glaciol.*, 51, 509 (2005). R. Thomas et al., *Geophys. Res. Lett.*, 33, L10503 (2006); E. Rignot, P. Kanagaratnam, *Science*, 311, 986 (2006); O. M. Johannessen, K. Khvorostovsky, M. W. Miles, L. P. Bobylev, *Science*, 310 (2005), p. 1013.

⁵⁰ Robert Bindshadler, "The environment and evolution of the West Antarctic ice sheet: setting the stage," *Philosophical transactions*, Series A, Mathematical, physical, and engineering sciences, 364, no. 1844 (July 15, 2006), pp. 1583-605; D J Wingham et al., "Mass balance of the Antarctic ice sheet," *Philosophical transactions*, Series A, Mathematical, physical, and engineering sciences, 364, no. 1844 (July 15, 2006) pp. 1627-35;

⁵¹ Anny Cazenave, "How Fast Are the Ice Sheets Melting?" *Science*, 314, no. 5803 (November 24, 2006), pp. 1250-1252.

⁵² See [http://nsidc.org/sotc/sea_ice.html].

⁵³ Eric V. Regehr, Steven C. Armstrup, and Ian Stirling, *Polar Bear Status in the Southern Beaufort Sea*, U.S. Geological Survey (Reston, VA, 2006).

(unaffected by vertical land movement) is attributable to expansion of the oceans' waters as they warm, and inflow of water from melting glaciers.⁵⁴

Likely Causes of Global Climate Change

The evidence is strong that the Earth's climate is changing; the forces thought to be driving observed climate changes are discussed below, including the evidence that human activities, particularly greenhouse gas emissions, have contributed a large influence on top of ongoing natural variability.

The Earth's climate is driven by the energy balance of the Sun's radiation coming into and leaving the Earth's atmosphere. The more active the Sun, the closer the Earth to the Sun, or the greater the ability for the Sun's energy to penetrate the atmosphere and be absorbed by the Earth, the greater will be the warming tendency on Earth. On the other hand, the less active the Sun, the farther the Earth is from the Sun, the more the Earth's atmosphere or surface reflect the radiation back out to space, the greater the cooling tendency. The tilt of the Earth's axis in its orbit around the Sun, making one or the other hemisphere closer to the Sun most of the year, drives the heating and cooling of the seasons outside of the tropics. Scientists understand well the fundamental drivers of the Earth's climate through geologic time; for example, how the pattern of an irregular orbit around the Sun has led to regular climate swings in and out of ice ages, or how massive volcanic eruptions can spew particles into the atmosphere that block incoming radiation and cause temporary cooling.

Until human populations grew to large numbers — from a population of about 5 million around 10,000 years ago to over 6 billion today — the global climate was almost certainly not influenced by human activities. However, human clearing of land, use of fossil fuels for energy, and other activities have greatly changed the surface of the Earth and the composition of the atmosphere, leading almost certainly to changes the Earth's climate through the past 150 years. During this period, the population grew from about 1.3 billion in 1850 to about 6.5 billion today,⁵⁵ associated with land clearing, increasing affluence, a switch from wood to fossil fuels, and industrialization — all increasing greenhouse gas emissions and atmospheric concentrations. The IPCC science assessment concluded in 2007 that “most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.”⁵⁶

⁵⁴ Anthony A. Arend et al., “Rapid Wastage of Alaska Glaciers and Their Contribution to Rising Sea Level,” *Science*, 297, no. 5580 (July 19, 2002) pp. 382-386.

⁵⁵ See [<http://www.census.gov>].

⁵⁶ Intergovernmental Panel on Climate Change Working Group I, *Climate Change 2007: The Physical Basis* (Cambridge, UK: Cambridge University Press, 2007), [<http://ipcc-wg1.ucar.edu/>].

The Concept of Radiative and Other Forcing of the Earth's Climate

To compare the contributions of different agents to the balance of incoming and outgoing energy, scientists use the concept of *radiative forcing*, which quantifies the *direct* or *indirect* effect an agent has on global mean temperature. This concept has proved successful in helping to predict global temperatures. A shortcut for radiative forcing that is easier to compute and considered broadly reliable and, hence, is often used to compare greenhouse gases is *Global Warming Potential* (GWP). GWP is an index of how much a greenhouse gas may, by its potency and quantity, contribute to global warming over a period of time, typically 25, 75, or 100 years. *Non-radiative forcing* is an as-yet-unquantified concept of the effect on the Earth's energy balance that does not directly and immediately involve radiation, such as the effects of an increase in evaporation resulting from agricultural irrigation.

A 2005 panel of the National Academy of Science (NAS) concluded that the concept of radiative forcing is too limited to express contributions of different agents to regional climates, variability, or aspects of the climate system other than mean global temperature. For example, there is no measure of the influence of agents on precipitation, winds, or other important aspects of climate that may changedifferently than temperature. The NAS panel concluded that broader concepts are needed to more fully describe the influences of different agents on multiple aspects of climate. (National Research Council, *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties*, Washington: National Academies Press, 2005.)

The remainder of this section summarizes scientific knowledge of how human activities influence climate change; the human components are described because these are most readily addressed by public policies. In addition, greenhouse gases are particularly implicated in recent climate change and are the target of numerous programs and proposals intended to stabilize climate change. Natural forcings, over which humans generally have limited control, are discussed in **Appendix A**. Methods to compare the relative roles of human and natural forcings and conclusions that attribute a large part of observed warming to human activities are discussed at the end of this section.

The terms *radiative forcing*,⁵⁷ *non-radiative forcing*, and *GWP* (see “The Concept of Radiative and Other Forcing of the Earth's Climate” above), will be used in the following sections to explain and compare the contributions of different agents to observed and future climate change. A forcing may lead to a change in climate. In response to the climate change, other components of the Earth system may also adjust, resulting in *feedbacks* to the climate that can either *amplify* (*positive feedbacks*) or *dampen* (*negative feedbacks*) the initial change in climate. A number of researchers have concluded from observing natural forcings and variability that

⁵⁷ National Research Council, *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties* (Washington: National Academies Press, 2005).

large climate changes can be triggered by very small changes in forcings because of feedbacks that *amplify* the initial change.⁵⁸

Human Activities that Influence Climate Change

Virtually all climate scientists agree that human activities have changed the Earth's climate, particularly since the Industrial Revolution.⁵⁹ Consumption of fossil fuels and clearing of land, as well as industrial and agricultural production release so-called *greenhouse gases* (GHG). Other human-related influences on climate include air pollution, such as tropospheric ozone and aerosols (tiny particles), land use change, paving and urban development, and airplane emissions. The different ways in which humans are affecting climate change are discussed in the following sections.

Greenhouse Gases. Greenhouse gas concentrations in the Earth's atmosphere have increased dramatically since the Industrial Revolution, with carbon dioxide growing from about 280 ppm in 1850 to about 380 ppm today.⁶⁰ The presence of greenhouse gases is critical to trapping the Sun's energy and warming the planet to habitable temperatures. Human activities, such as use of fossil fuels, production of crops and livestock, and manufacture of various products, now emit certain gases in sufficient quantities to have raised concentrations higher than they have been for hundreds of thousands of years; the elevated concentrations are changing the balance of solar radiation in and out of the Earth's atmosphere and, consequently, altering the Earth's climate.

Greenhouse gases (GHG) in the atmosphere allow the Sun's short wave-length radiation to pass through to the Earth's surface, but once the radiation is absorbed by the Earth and re-emitted as longer wave-length radiation, GHG trap the heat in the atmosphere. The best-understood greenhouse gases include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and certain fluorinated compounds, including chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC), hydrofluorocarbons (HFC),⁶¹ perchlorofluorocarbons (PFC), and sulfur

⁵⁸ R.B. Alley et al., "Abrupt Climate Change," *Science*, 299 (March 28, 2003), pp. 2005-2010.

⁵⁹ National Research Council, *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties* (National Academies Press, 2005); S. Fred Singer, "Human Contribution to Climate Change Remains Questionable," *EOS Transactions*, 80 (April 20, 1999), pp. 183-187.

⁶⁰ Neftel, A., H. Friedli, E. Moor, H. Lötscher, H. Oeschger, U. Siegenthaler, and B. Stauffer, 1994, *Historical CO₂ record from the Siple Station ice core*, in *Trends: A Compendium of Data on Global Change*, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy (Oak Ridge, TN). Also, World Data Centre for Greenhouse Gases (WDCGG), *WMO Greenhouse Gas Bulletin: The State of Greenhouse Gases in the Atmosphere Using Global Observations through 2005* (Geneva, 2006), at [<http://gaw.kishou.go.jp/wdcgg.html>].

⁶¹ The production of CFC and HCF and additional substances is regulated by the EPA in compliance with the Montreal Protocol to Protect the Stratospheric Ozone Layer, its London Amendment, and other subsidiary international treaties. Because they are covered by the (continued...)

hexafluoride (SF₆).⁶² These greenhouse gases remain in the atmosphere for decades to thousands of years and are generally *well-mixed* around the globe; hence, their warming effects are largely global. (See “The Concept of Radiative and Other Forcing of the Earth’s Climate” above). Moreover, the long atmospheric residence time and the cumulative effects of gases have important implications for possible policy responses. (See “Time Lags in the Climate System” below). Because these GHG affect radiative balance of the Earth in similar ways, they can be compared using measures of *radiative forcing* or *Global Warming Potentials* (GWP),⁶³ the latter being an easier but imperfect approximation.

The following human-related sources of the principal greenhouse gas emissions have been identified:

- Carbon dioxide (CO₂): combustion of fossil fuels, solid waste, wood, and wood products; cement manufacture. Human activities can also enhance or reduce removals of CO₂ from the atmosphere by vegetation and soils (e.g., via reforestation or deforestation).
- Methane: coal mining, natural gas handling, trash decomposition in landfills, and digestion by livestock. Significant natural sources include wetlands and termite mounds.

⁶¹ (...continued)

Montreal Protocol and subsidiary agreements, they are not covered by the Kyoto Protocol, nor by many proposals for reductions of GHG emissions. However, there may be opportunities to reduce their emissions further.

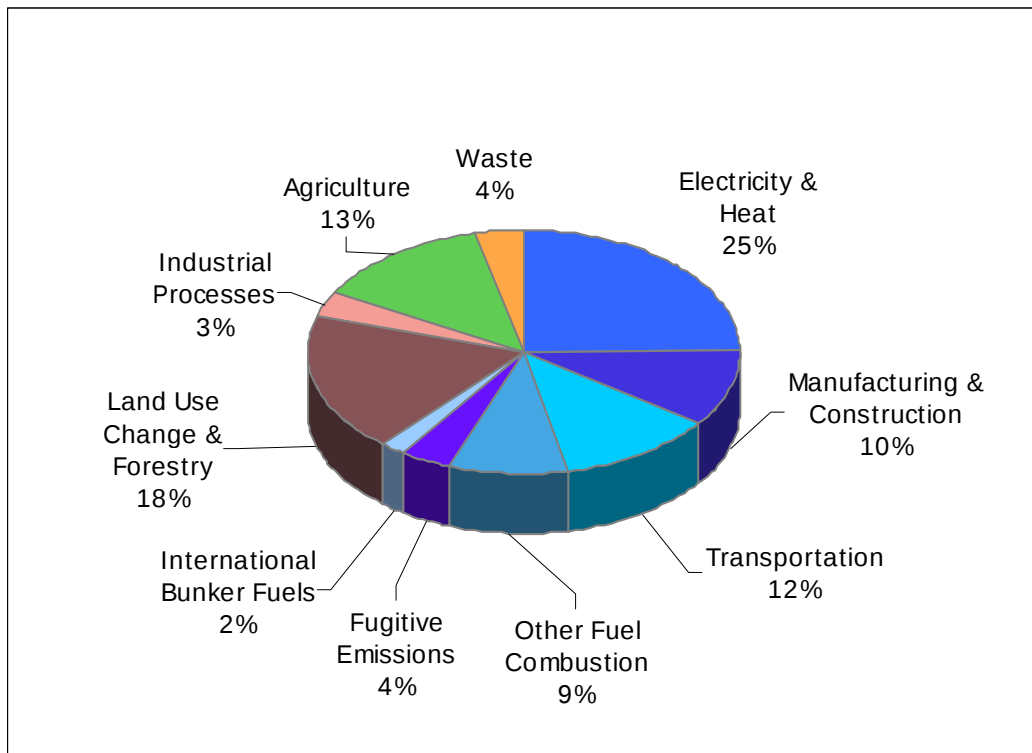
⁶² Water vapor is the most important greenhouse gas but is only indirectly affected by human activities, as discussed in **Appendix A**. Additional pollutant emissions indirectly affect climate change largely on the local to regional scale, including carbon monoxide (CO), nitrogen oxides (NO_x) and non-methane volatile organic compounds (NMVOC), and particulate matter or aerosols. NO_x and NMVOC, as well as methane (CH₄), contribute to ozone pollution (smog) in the troposphere, which is a greenhouse gas. Aerosols, which are extremely small particles or liquid droplets, such as those produced by emissions of SO₂ or elemental carbon, can also strongly affect the absorption or reflection of radiation in the atmosphere. Substances that deplete the stratospheric ozone layer, such as chlororfluorocarbons (CFC), also indirectly affect the climate, because the loss of stratospheric ozone causes local cooling and changes the patterns of temperatures and atmospheric circulation. These radiatively important pollutants are controlled, to varying degrees, by regulations in many countries (including the United States under the Clean Air Act).

⁶³ GWPs are a useful but imperfect shortcut for radiative forcing. They are calculated using the potency of the radiative effect of one unit of a GHG times its potency, integrated over the atmospheric lifetime of that GHG. GWPs require selecting a time period (typically 25, 75, or 100 years) over which the effects are taken into account. In other words, using 25-year GWPs gives greater emphasis to the forcings that are potent but short-lived in the atmosphere (e.g., methane), having greater effect on short-term global warming; the 100-year GWPs give greater emphasis to the gases that last in the atmosphere for decades to a hundred years (e.g., carbon dioxide), having greater effect on century-scale global warming.

- Nitrous oxide (N₂O): nitrogen fertilizers, certain industrial manufacturing, and combustion of solid waste and fossil fuels.
- Chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF₆): commercial, industrial, and household products.

The share of emissions coming from each sector varies greatly by gas. **Figure 4** reflects the fact that agricultural production contributes very little to carbon dioxide emissions (aside from land clearing), but is about 62% of nitrous oxide emissions globally, mainly from fertilizer use.

Figure 4. Sectoral Shares of Global GHG Emissions in 2000



Source: Data extracted from Climate Analysis Indicators Tool (CAIT) version 4.0 (Washington: World Resources Institute, 2007), available at [<http://cait.wri.org>].

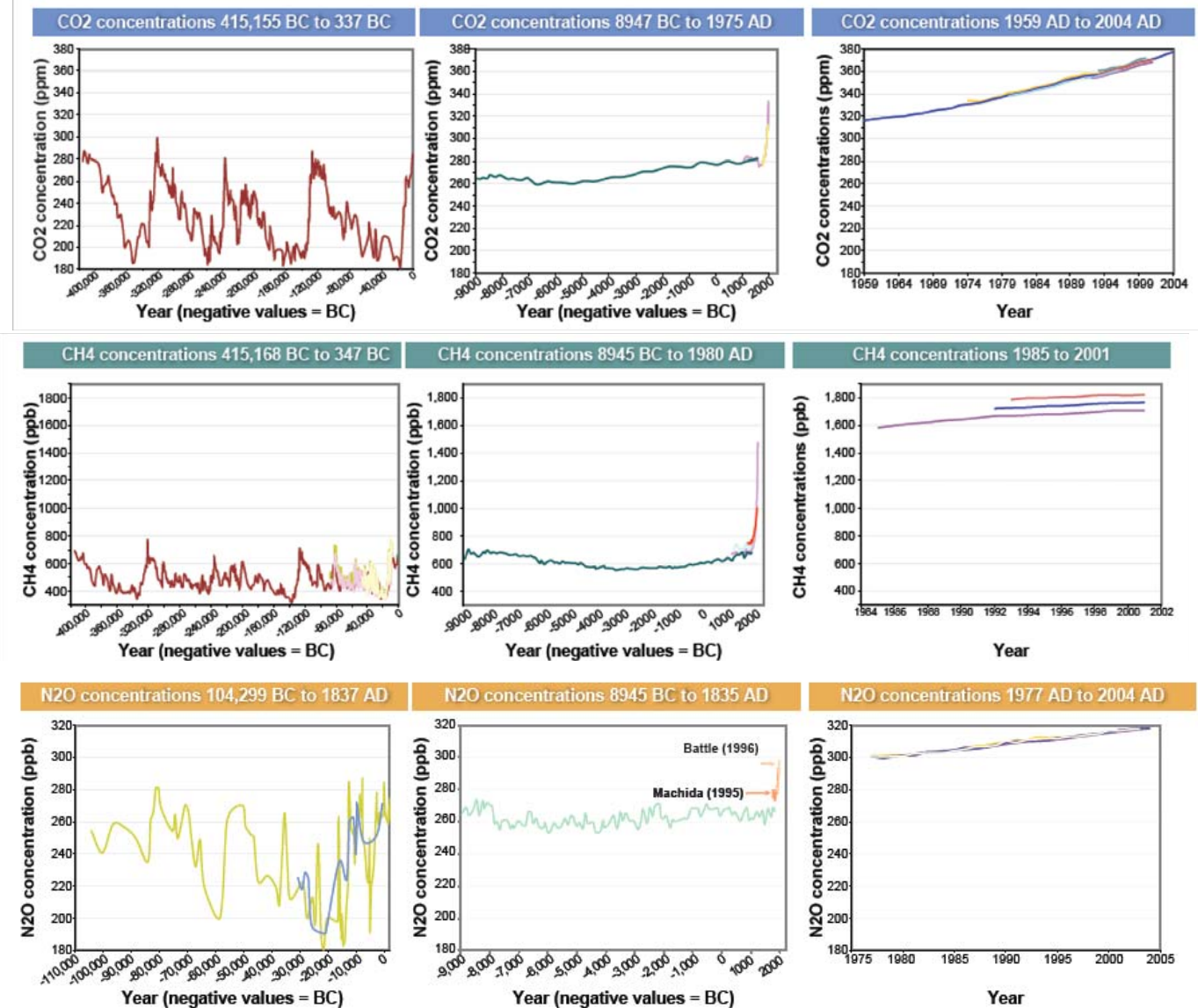
Notes: The GHG emissions included in this data set are CO₂, CH₄, N₂O, HFC, HCFC, and SF₆, from human-related sources only. Other greenhouse gases, such as tropospheric ozone, are not emitted directly and so cannot be tallied as emissions. In addition, the CFC, HCFC, and other pollutants limited by the Convention to Protect the Stratospheric Ozone are not included in this count; their influence is still significant but declining under control programs. Nor does this figure include emissions of aerosols, including sulfates, black carbon, and organic carbon, which may have strong temporary and regional effects that cannot be quantified comparably with the long-lived gases represented in this figure.

For the year 2000,⁶⁴ CO₂ constitutes approximately 72% of the human contribution to GHG emissions; CH₄ is about 18% and N₂O is about 9%. There is considerable uncertainty regarding some of the historical estimates, especially prior to the 1950s.

Although most of the GHG occur naturally to some degree, the human-driven emissions of GHG are increasing above the rate of their natural removals from the atmosphere. Scientists are certain that GHG emissions from human activities have increased GHG concentrations in the atmosphere to levels unprecedented for hundreds of thousands, possibly even millions, of years. Over the past 150 years, CO₂ concentrations have increased globally by more than one-third, from about 280 ppm to current levels of about 380 ppm (**Figure 5**).⁶⁵ Methane has increased by about 150%, although the rate of increase has declined over the past decades, down to essentially no growth (varying slightly) in recent years. N₂O concentrations have increased by 16% since the Industrial Revolution. (For data sourcing, see **Figure 5**.)

⁶⁴ Data source: Emission Database for Global Atmospheric Research version 3.2, Fast Track 2000 Project, using 100-year GWPs.

⁶⁵ For reference, the UN Framework Convention on Climate Change (UNFCCC), an international treaty signed by the United States and ratified by the Congress in 1992, establishes an objective of “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.” (Art 2) (1) Although science can help to identify the degree of “interference” and implications of climate changes at different concentration levels or degrees of temperature change, most scientists agree that the determination of “dangerous” is a political decision, not one that can be objectively decided by scientists. A number of proposals of stakeholders in the United States and other countries most often aim to stabilize carbon dioxide concentrations in the atmosphere at levels of 450, 550, or 650 ppm. Some scientists suggest that current levels already have exceeded the “dangerous” threshold.

Figure 5. CO₂, Methane and Nitrous Oxide Concentrations over 400,000 Years Ago to 2004

Source: Data accessed through the Carbon Dioxide Information Analysis Center (CDIAC), with full citations in footnote.⁶⁶

⁶⁶ This figures uses data sets from numerous individual studies of Barnola, J.-M., D. Raynaud, C. Lorius, and N.I. Barkov (2003), *Historical CO₂ record from the Vostok ice core*. Blunier, T. and E.J. Brook (2001), "Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period," *Science*, 291 (January 5, 2001), pp. 109-112. Chamard, P., L. Ciattaglia, A. di Sarra, and F. Monteleone (2001), *Atmospheric CO₂ record from flask measurements at Lampedusa Island*; James W. Elkins, James H. Butler, Thayne M. Thompson, Geoffrey S. Dutton, Stephen A. Montzka, Bradley D. Hall, Halocarbons and Other Atmosphere Trace Species Group (HATS) /CMDL/NOAA; D.M. Etheridge, L.P. Steele, R.L. Langenfelds, R.J. Francey, J.-M. Barnola and V.I. Morgan, (1998) *Historical CO₂ records from the Law Dome DE08, DE08-2, and DSS ice cores*; (continued...)

Tropospheric Ozone. Ozone is another greenhouse gas, but it is not emitted directly by humans. Although it occurs naturally, tropospheric ozone is elevated by polluting emissions, such as nitrogen oxides from fuel combustion or volatile organic compound (VOC) emissions from fuel leakage, solvent evaporation, etc. Tropospheric ozone concentrations, both background levels and episodes of high concentrations, have been increased, perhaps 50%, by polluting emissions since the Industrial Revolution.⁶⁷ Ozone forms and dissipates quickly, so its concentrations are unevenly distributed in time and space; hence it is difficult to compare the forcing of troposphere ozone with other GHG through *Global Warming Potentials*. Tropospheric ozone pollution drifting into the Arctic region may be responsible for one-third to one-half of the warming observed in its springs and summers.⁶⁸ In many countries, ozone concentrations are controlled by regulations that limit air pollutant emissions, such as the Clean Air Act in the United States.

Sulfur and Carbon Aerosols. Aerosols are tiny particles suspended in the air; some are there from natural sources, such as volcanoes and forest fires, whereas others result from human pollution, such as emissions from powerplants or vehicles. The principal aerosols of concern to climate change are sulfates, black carbon, and organic carbon. Aerosols can scatter or absorb light, with cooling or warming effects, respectively, depending on the size, color, composition, and other characteristics of aerosols. Black carbon aerosols are thought primarily to warm the atmosphere; organic carbon aerosols (emitted largely by forest fires) are thought to have mostly a cooling effect.

⁶⁶ (...continued)

Flückiger, J., E. Monnin, B. Stauffer, J. Schwander, T.F. Stocker, J. Chappellaz, D. Raynaud, and J.-M. Barnola (2002), "High resolution Holocene N₂O ice core record and its relationship with CH₄ and CO₂," *Glob. Biogeochemical Cycles*, volume 16, no. 1 (March 2002), 10.1029/2001GB001417; Hashita et al.; Keeling, C.D. and T.P. Whorf (2005), *Atmospheric CO₂ records from sites in the SIO air sampling network*; Neftel, A., H. Friedli, E. Moor, H. Lötscher, H. Oeschger, U. Siegenthaler, and B. Stauffer (1994), *Historical CO₂ record from the Siple Station ice core*; Petit, J.R. et al. (2001), *Vostok Ice Core Data for 420,000 Years*, IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series #2001-076, NOAA/NGDC Paleoclimatology Program (Boulder, CO); Sowers, T., R.B. Alley, and J. Jubenville (2003), "Ice Core Records of Atmospheric N₂O Covering the Last 106,000 Years," *Science*, vol. 301, no. 5635, pp. 945-948 (August 15, 2003); Steele, L. P., P. B. Krummel, and R. L. Langenfelds (2002), *Atmospheric CO₂ concentrations from sites in the CSIRO Atmospheric Research GASLAB air sampling network* (October 2002 version); Thoning, K.W. and P.P. Tans (2000), *Atmospheric CO₂ records from sites in the NOAA/CMDL continuous monitoring network*. All in *Trends: A Compendium of Data on Global Change*, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy (Oak Ridge, TN), at [<http://cdiac.ornl.gov/trends/trends.htm>].

⁶⁷ Larry W. Horowitz, "Past, present, and future concentrations of tropospheric ozone and aerosols: Methodology, ozone evaluation, and sensitivity to aerosol wet removal," *Journal of Geophysical Research*, 111, no. D22211 (November 21, 2006).

⁶⁸ Shindell, D.T., G.A. Schmidt, R.L. Miller, and D. Rind, "Northern Hemisphere winter climate response to greenhouse gas, ozone, solar, and volcanic forcing," *J. Geophys. Res.*, 106 (2001) pp. 7193-7210.

Sulfur aerosols (sulfates) scatter incoming solar radiation and have consequent cooling influence on climate. This has been well known for decades but only included in climate modeling since the early 1990s. Sulfate aerosols are a by-product of sulfur emissions, largely from the burning of coal and oil, as well as some industrial processes. Sulfur emissions and their aerosols have increased dramatically over the past century.

Aerosol effects on temperature are both regional and short-lived (as particles typically remain suspended in the atmosphere for days to weeks). Aerosol concentrations in the atmosphere fluctuate greatly, are difficult to measure, and consequently are uncertain by a factor of two or more. Aerosols are also understood to affect precipitation patterns downwind of their emissions, although research is just beginning to reveal the processes involved; they may influence monsoon water cycles⁶⁹ as well. Aerosols may have amplifying or dampening effects when interacting with such factors as sea surface temperatures⁷⁰ and snow cover.⁷¹ The role of aerosols in driving various aspects of climate is one of the major uncertainties being tackled by monitoring and research.

Emissions from Aviation. Emissions from fuel consumption by aircraft and water vapor emissions in their exhaust both contribute to climate change in special ways. First, these GHG are emitted at high altitudes, where few other GHG are present, and therefore do not overlap other gases' absorbing spectra, increasing their relatively small contribution to global surface temperatures. They also affect the vertical distribution of temperatures in the atmosphere. More complex, the emissions of small particles and water vapor form ice crystals in aviation *contrails* that can produce more clouds in the upper troposphere. These clouds can have a cooling or warming effect depending on the characteristics of the ice crystals; most scientists believe that the overall climate effect of contrails is a net warming. These are not globally distributed and therefore have stronger regional than global effects.

Land Surface Changes. Although the Earth's land surface changes naturally, as part of ecosystem processes, humans have had a major impact on land cover and land uses that, in turn, affect the climate system. At least one scientist has provided evidence that human forest clearing and rice production, beginning roughly 8,000 and 5,000 years ago, respectively, may have significantly affected carbon dioxide and methane concentrations, as could the carbon sequestration from forest regrowth following abandonment of farms in Medieval times after the bubonic plague.⁷²

⁶⁹ Lau, K.-M., and K.-M. Kim, "Observational relationships between aerosol and Asian monsoon rainfall, and circulation," *Geophysical Research Letters*, 33 (2006) (L21810).

⁷⁰ Sydney Levitus et al., "Warming of the World Ocean, 1955-2003," *Geophysical Research Letters*, 32 no. 02604 (2005).

⁷¹ James Hansen and Larissa Nazarenko, "Soot climate forcing via snow and ice albedos," *PNAS*, 101, no. 2 (January 13, 2004), pp. 423-428.

⁷² William F. Ruddiman, "The Anthropogenic Greenhouse Era Began Thousands of Years Ago," *Climatic Change*, 61, no. 3 (December 2003), pp. 261-293.

Land Clearing. When humans clear land, as happened in the United States from its early years and well into the 20th Century, CO₂ is emitted mostly through burning or decomposition, increasing CO₂ concentrations in the atmosphere. As vegetation regrows, it absorbs CO₂ from the atmosphere, albeit more slowly than emission occurred. Net deforestation is occurring globally, mainly in developing countries. The United States, like many other countries, cleared land decades ago but abandoned some of it with industrialization and migration to more fertile lands; regrowth of forests on abandoned lands is, in net, estimated to be removing CO₂ from the atmosphere. In other words, U.S. forests overall are a net *sink* for carbon, not a *source* at this time, on the order of 780 million metric tonnes of CO₂ per year.⁷³ Agriculture currently covers about one-third of the Earth's land surface. Agriculture can also alter the evaporation and transpiration of plants on land, and can alter local to regional climates, and, via atmospheric circulation, possibly modify global climate as well.

Land Cover Feedbacks. Land cover change also results from climate change, and therefore can be a *feedback* within the climate system. On the one hand, CO₂ in the atmosphere is effectively a nutrient to plants, and this higher *carbon fertilization* will tend to increase vegetation growth and remove more CO₂ from the atmosphere. Where precipitation increases, and, to a lesser degree, where currently cool locations warm, vegetation is expected to increase, creating a negative feedback to climate warming. To the degree that vines and other weedy plants thrive better in higher CO₂ and warmer temperatures than woody trees, the enhanced carbon uptake may be short-lived. Moreover, warmer temperatures and greater moisture will tend to speed up decomposition, and even potentially cause die-back at high levels, generating a positive feedback to climate warming. In addition, trees and other vegetation transpire water vapor (another GHG) into the atmosphere. Also, land cover can alter the amount of dust raised by wind into the atmosphere.

Albedo. The reflectivity of the Earth's surface is called *albedo*. Where the Earth's surface has low albedo (i.e., is not very reflective), the Sun's radiation is absorbed and warms the surface. Particles deposited on the snow/ice surface (e.g., from pollution) can darken the surface and increase melting. In places covered with snow or ice, the surface has very high albedo; as the extent of snow and ice diminishes with climate warming, the reflectivity decreases and creates a positive feedback to climate, leading to more warming. Land cleared of its vegetation may reflect light more than the dark leaves that previously shaded it, increasing reflection of solar energy, and having a cooling impact. When snow is on the ground, the removal of trees can have a particularly strong albedo cooling effect, but mostly in winter or locations with permanent snow or ice. Land clearing tends to warm temperatures near the equator and cool them at high latitudes.⁷⁴

⁷³ U.S. Environmental Protection Agency, *The U.S. Inventory of Greenhouse Gas Emissions and Sinks: Fast Facts* (Washington , 2006).

⁷⁴ N. Ramankutty, C. Delire, and P. Snyder, "Feedbacks between agriculture and climate: An illustration of the potential unintended consequences of human land use activities," *Global and Planetary Change*, 54 (July 2006), pp. 79-93.

Methods To Compare Human and Natural Causes

Multiple factors simultaneously influence the Earth's climate, and scientists have developed a variety of methods that help determine which forcings are contributing, and are likely most important, at any period. Several different lines of evidence discovered in the past decade have led a large majority of scientists to conclude that human-related greenhouse gas emissions have contributed substantially to the increase in global mean temperature and other climate changes observed since the 1970s, and probably over the past century. Additional factors also contribute, including solar variability, volcanoes, and natural variability.

The simplest method of analyzing the role of greenhouse gases in climate change is to compare CO₂ concentrations in the atmosphere with surface temperatures. Through the past million years or more, CO₂ and CH₄ concentrations have been tightly correlated with global temperatures in the paleologic records.⁷⁵ This correlation may be insufficient to discern the triggering cause of the changes, but most scientists are confident that once warming has been initiated, there are strong positive feedbacks to CO₂ levels and again to climate warming, leading to a strongly amplifying effect of the initial cause.⁷⁶ This would explain instances of timing mismatches, where rising CO₂ concentrations lag behind rising temperatures, evidenced in the paleoclimatological record. However, some scientists also raise problems in the proxy records, pointing to time lags among the complex interactions within the climate system, and to additional drivers of change that, at times, may exceed the forcing of CO₂ in the atmosphere.⁷⁷

Another method scientists use to attribute climate change to various sources, or to project future changes, relates to the concept of causative radiative forcing. **Figure 6** shows an estimation of the relative contributions of GHG and other agents to radiative forcing from 1950 to 2000.⁷⁸ The apparent strength of greenhouse gas forcing has steadily grown and seems to dominate other known forcings in its effects on warming the Earth's climate. Volcanic emissions of stratospheric aerosols are also major but episodic and short-lived drivers. Tropospheric aerosols, including sulfates, black carbon, and organic carbon have had a much smaller but growing cooling effect. From these data, the effect of solar variability on recent temperature change is apparent, but small. Some scientists, however, contend that solar variability has a larger role.

⁷⁵ European Project for Ice Coring in Antarctica (EPICA), at [http://www.esf.org/esf_article.php?activity=1&article=85&domain=3]; Isabel P. Montanez et al., "CO₂-Forced Climate and Vegetation Instability During Late Paleozoic Deglaciation," *Science*, 315, no. 5808 (January 5, 2007), pp. 87-91.

⁷⁶ For example, Heiko Palike et al., "The Heartbeat of the Oligocene Climate System," *Science*, 314, no. 5807 (December 22, 2006), pp. 1894-1898.

⁷⁷ Thomas J. Crowley and Robert A. Berner, "CO₂ and Climate Change," *Science*, 292, no. 5518 (May 4, 2001), pp. 870-872; Lee R. Kump, "Reducing uncertainty about carbon dioxide as a climate driver," *Nature* 418 (September 12, 2002), pp. 188-190.

⁷⁸ J. Hansen et al., *Journal of Geophysical Research*, 107, D18, 4347, (2006).

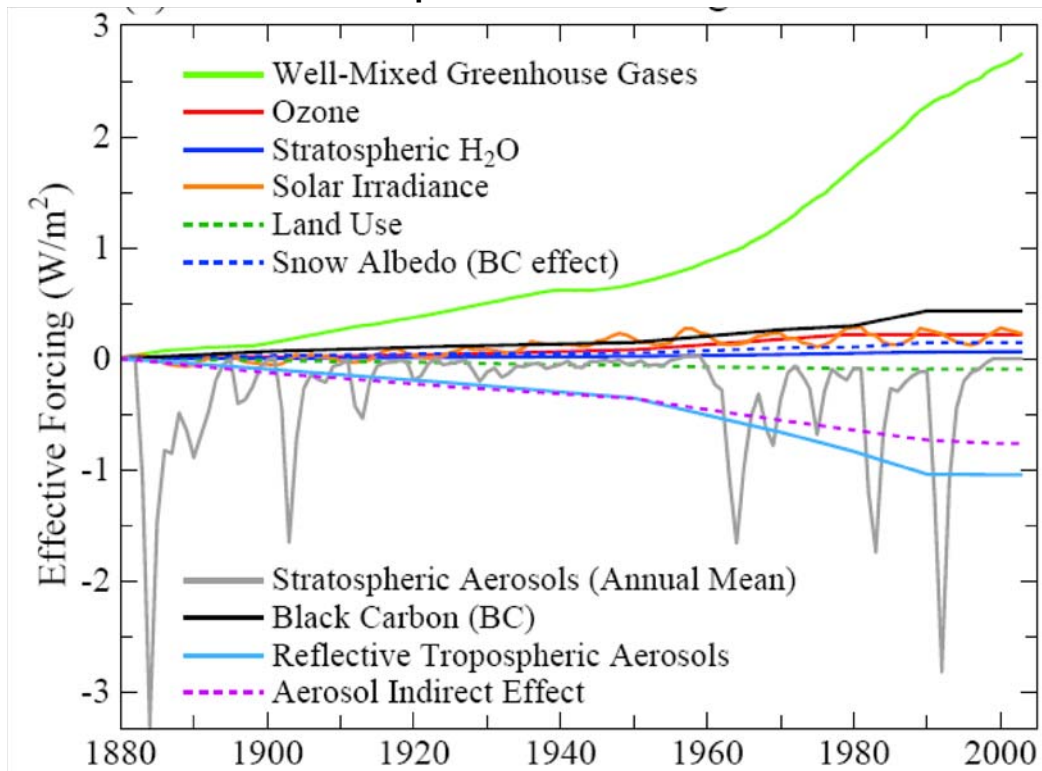
A third method scientists have developed, especially since 2000, is the concept of *fingerprinting* the patterns of radiative forcing and observed change, and comparing them.⁷⁹ Different forcing agents produce different patterns of climate change over time and space, and even vertically in the atmosphere. For example, volcanoes spew aerosols that persist only a few years in the atmosphere, creating a temporary cooling effect over both land and oceans. Reductions in solar irradiance can last decades and affect land temperatures more than oceans. These patterns are very different from, for example, the influence of long-lived greenhouse gases that are expected to exert long-lived, global influence.

The observed warming of the climate, described above in “Changes Observed in the Earth’s Climate,” corresponds to expected greenhouse gas-induced patterns of warming greater in winter than summer, more at night than daytime, and of generally increasing precipitation, and more warming at high latitudes than low latitudes. Another piece of evidence is the observed cooling, as expected, at 50 km and higher in the atmosphere, which cannot be explained by seasonal or solar cycles. Also, the increasing heat content of the oceans cannot be explained by urban heat islands or other placement-related problems with measurement stations. *Fingerprint* methods have proven critical in attributing the climate change over the past decades to greenhouse gas emissions versus natural forcings.

Several studies have tried to explain historical climate change by running computer models — mathematical simplifications of how scientists understand climate processes to work — with different combinations of forcing agents. (See “Use of Models for Climate Change Analysis” below.) The results from one are presented in **Figure 6**. Scientists have repeatedly found that they cannot reproduce the warming of the last half century with natural forcings alone, but can generate warming patterns similar to observed climate changes when including greenhouse gases and aerosols. These studies constitute one of the important lines of evidence that lead scientists to conclude that recent climate change has been caused in large part by greenhouse gases.

⁷⁹ D.T. Shindell et al., “Volcanic and solar forcing of climate change during the preindustrial era,” *Journal of Climate*, 16 (2003), pp. 4094-4107.

Figure 6. Estimated Effects of Different Forcings on Global Temperature Since 1880



Source: J. Hansen et al., JGR, 107, D18, 4347, 200.

Attribution of Climate Change in the 20th Century

In conclusion, a variety of natural and human-related forces have influenced observed climate change throughout the 20th Century, including greenhouse gases accumulating in the atmosphere, other air pollutants, land use change, solar variability, and volcanoes. The relative importance of each of these factors is not well quantified.⁸⁰ Nonetheless, relying on a variety of tests, a preponderance of scientists have concluded that the observed climate change over the 20th Century cannot be explained without including the effects of rising concentrations of greenhouse gases. A panel of the National Academy of Science, at the request of President George W. Bush, reviewed the established research in 2001 and concluded that

the changes observed over the last several decades are likely mostly due to human activities, but we cannot rule out that some significant part of these changes is also a reflection of natural variability.⁸¹

⁸⁰ Thomas L. Delworth and T.R. Knutson, "Simulation of Early 20th Century Global Warming," *Science*, 287, no. 5461 (March 24, 2000), pp. 2246-2250.

⁸¹ National Research Council, *Climate Change Science: An Analysis of Some Key Questions* (Washington: National Academies Press, 2001), p. 1.

The attribution to greenhouse gas forcing of significant climate change since the 1970s has been strengthened since the NRC 2001 findings by a number of additional studies, including matching of the spatial and temporal patterns of greenhouse gas forcing with observed ocean heat distribution.⁸² The IPCC science assessment concluded in 2007 that “most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.”⁸³

Projections of Future Human-Driven Climate Change

Much of the discussion of future climate change is based on projections produced by computer models that represent as completely as possible the relevant factors that are today understood to influence the climate (including the effects of past climates). These models are incomplete, as scientific understanding of the relevant factors and processes is continuously developing. However, climate models have improved substantially over the past decade, and experts believe that many now do a better job of representing the current and historical climates. It is disagreement about the ability of these models to predict future climate change that drives much of the current climate change debate. This section explains how projections of climate are produced and provides the range of forecasts provided by the many climate analysis institutions around the world.

Most studies indicate, and experts generally agree, that growth of greenhouse gas forcing, if it continues unabated, will raise global average temperatures well above natural variability. The 2007 IPCC scientific assessment concluded, “[F]or the next two decades a warming of about 0.2°C [0.36°F] per decade is projected for a

⁸² Tim P. Barnett et al., “Penetration of Human-Induced Warming into the World’s Oceans,” *Science*, 309, no. 5732 (July 8, 2005), pp. 284-287. See also B D Santer et al., “Contributions of anthropogenic and natural forcing to recent tropopause height changes,” *Science*, 301, no. 5632 (July 25, 2003), p. 479. Gerald A. Meehl et al., “Combinations of Natural and Anthropogenic Forcings in Twentieth-Century Climate,” *Journal of Climate*, 17 (October 1, 2004), pp. 3721-3728. Pet D.T. Shindell et al., “Volcanic and solar forcing of climate change during the preindustrial era,” *Journal of Climate*, 16 (2003), pp. 4094-4107; S. Fred Singer, “Human Contribution to Climate Change Remains Questionable,” *EOS Transactions*, 80 (April 20, 1999), pp. 183-187. A. Stott et al., “Observational Constraints on Past Attributable Warming and Predictions of Future Global Warming,” *Journal of Climate*, 29 (July 1, 2006); Simon F.B. Tett et al., “Causes of twentieth-century temperature change near the Earth’s surface,” *Nature*, 399 (June 10, 1999), pp. 569-572.

⁸³ Intergovernmental Panel on Climate Change Working Group I, *Climate Change 2007: The Physical Basis* (Cambridge, UK: Cambridge University Press, 2007), [http://ipcc-wg1.ucar.edu/].

range of [SRES]⁸⁴ emission scenarios. Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C [0.2°F] would be expected.” It further found, “[T]he best estimate for the low [SRES] greenhouse gas emission] scenario (B1) is 1.8°C (likely⁸⁵ range is 1.1°C to 2.9°C) [3.2°F (likely range is 2.0°F to 5.2°F)], and the best estimate for the high scenario (A1F1) is 4.0°C (likely range is 2.4°C to 6.4°C) [5.2°F (likely range is 4.3°F to 9.5°F)].” It will be many years to decades before the wide range of uncertainty in global average temperature increases can be narrowed with confidence. (See “Use of Models for Climate Analysis” below.)

Climate models generally predict more heat waves, droughts, and floods; extreme cold episodes are predicted to decrease; the centers of continents are likely to experience summer warming and dryness. Scientists expect precipitation will be more intense when it occurs (therefore also increasing runoff and the risk of flooding).⁸⁶ But it will be substantially harder to establish the range of possible changes in the hydrologic cycle — or even direction of change for some regions — both because there are fewer historical observations on which to build scientific understanding, and because the physical constraints are weaker. Scientists expect atmospheric and ocean circulation are likely to change as well.

Studies have found that future climate change will not be evenly distributed geographically or temporally: even if the global mean temperature were to change very little, regional climate changes could be dramatic because of the uneven distribution of forcings by different agents and the connectedness of regions within the climate system. Although almost all regions are expected to experience warming, some regions are projected to become wetter while others become drier.

Future climate change is not likely to proceed smoothly, as often depicted by averaged model results, but to swing up and down around a rising average, as has occurred in the past. This variability around a rising average may complicate the detection and prediction of change. Though the ability of scientists to understand and model changes is advancing, there will remain major uncertainties in the forecasting of local and seasonal climate changes that accompany global warming. Climate models are not yet adept at capturing extreme events or abrupt changes, and there is significant potential of important climate “surprises” that models may not predict. It is unclear how serious future changes may be, given the climate variability to which humans and ecosystems are already adapted.

⁸⁴ Special Report on Emission Scenarios of the IPCC (2000). This report estimates greenhouse gas emissions and uptake with a variety of plausible, no-control-policy assumptions over the 21st century.

⁸⁵ “Likely” means greater than 66% likelihood.

⁸⁶ Kevin E. Trenberth et al., “The Changing Character of Precipitation,” *Bulletin of the American Meteorological Society* (September 2003), p. 1205.

Use of Models for Climate Change Analysis

In deciding whether to take action to address climate change, and what actions may be effective, decision-makers seek projections of what to expect in the future. Scientists cannot rely only on analogies to past climates because the Earth's current biological, chemical, and geologic systems, and human activities, have no precedent. Scientists use models, first, to understand the system they are studying, building from theory and validating with experiments and observations of the past, in order to interpret the causes of past variability and to use that understanding to forecast the future.

Models are simplified representations of systems. Almost all of the models used for climate change analysis are mathematical, and they are developed using a wide variety of disciplines, including physics, atmospheric chemistry, economics, engineering, ecology, and others. Over time, and especially in the past decade, different disciplines have joined expertise and tools to provide more integrated — and complete — models for analyzing climate change. As important, while climate models a few decades ago were built primarily on theoretical understanding, the recent expansion of monitoring, computing capacity, and funding has allowed *data assimilation*, or the use of real-world observations, to improve the models.

Rigorous comparisons of models help to validate their performance by reproducing observations of today's climate, although good performance on this test does not guarantee reliable future projections of climate changes or their patterns. Models are also tested in their ability to reproduce paleoclimatic events, and are compared in detail to understand why models respond differently to forcings.

Since the 1990s, climate models perform significantly better in reproducing current and historical climates, although models diverge in important ways in the patterns of climate that they produce. Since 2000, important improvements have been made in modeling changes in some regions, while large discrepancies exist for a few regions. Climate models are generally less successful in reproducing observed precipitation than temperature, perhaps because of its higher natural variability, and extreme events and local climate predictions require a higher resolution than global climate models currently offer. Also, different models produce different results. In long-term projections of climate change, the differences between climate models for a given GHG emission scenario can be larger than the differences produced by one model running the range of future GHG emission scenarios. Furthermore, there is some scientific opinion that, while research is critically important for improving scientific understanding of the climate system and for possible future changes, research may well increase the range of uncertainty, as new processes are uncovered or existing structures are tested and revised.

Methods and models are improving in their ability to characterize important uncertainties and to support risk assessment and risk management decisions in spite of the unknowns, just as in other sectors such as finance, security and medicine. The application of risk assessment and management techniques to climate change decision-making is nascent, but is providing useful insights for incorporating uncertainties into decision-making.

Another complication in forecasting climate change is the importance of feedbacks — both positive and negative. A National Research Council report concluded that feedbacks in the climate system have, many times in the geologic record, amplified small initial climate perturbations into major climate cycles with global mean temperature swings of 5° to 6°C.⁸⁷ The close linkage, over hundreds of thousand of years, between past temperature swings and carbon dioxide and methane concentrations in the atmosphere strongly suggests that temperature change can trigger strong positive amplifications through the carbon cycle and water vapor feedbacks. Current models include such feedbacks, but they are very uncertain. The most important and uncertain feedbacks affecting future climate projections include water vapor feedback, cloud feedbacks, vegetation feedbacks, and albedo.⁸⁸

Thus, while most climate scientists conclude with high confidence that future climate change, forced by greenhouse gases, land use change, and natural factors, is probable, the magnitude, rapidity, and details of the changes are likely to remain unclear for many years, or even decades. There is near unanimity among climate model projections that (1) past human emissions have committed the climate to some change over the next few decades,⁸⁹ and GHG emissions emitted from now on will begin to dominate global warming by mid-century, and (2) feedbacks to the carbon cycle tend to be positive, amplifying initial warming by greenhouse gases. The latter suggests also that climate change may reduce the effectiveness of carbon uptake by oceans and vegetation, and that more warming would require proportionately greater GHG emission reductions to stabilize the climate system.

Impacts of Projected Climate Change

Projected impacts of future climate change indicate that there will be winners and losers among regions, sectors, and income groups. Some groups may benefit from a certain amount of climate change, whereas others may suffer harm. Regions that fare relatively well may be negatively affected by changes in other regions through trade, security, and humanitarian demands and immigration pressures. Future generations are likely to experience more change, but may also be wealthier and hence better able to adapt, although not uniformly so. Many species may become extinct, while others are likely to flourish. The local effects of climate change may contribute more to decision-making than national or global aggregates.

In April 2007, the IPCC released its fourth assessment of the impacts of climate change and vulnerability to these impacts. Selected key findings from that report are provided in the box below.

⁸⁷ R.B. Alley et al., “Abrupt Climate Change,” *Science*, 299 (March 28, 2003), pp. 2005-2010.

⁸⁸ Feedbacks relating to human economies and population distributions may be very important as well. However, there are very few “integrated” models capable of exploring the physical and economic systems together.

⁸⁹ Wigley, T M L, “The Climate Change Commitment,” *Science*, 307, pp. 1766-1769.

IPCC Climate Change 2007: Selected Key Findings on Impacts, Adaptation and Vulnerability

Evidence from all continents and most oceans show that many natural systems are being affected by regional climate changes, such as —

- enlargement and increased numbers of glacial lakes, ground instability in permafrost regions, rock avalanches and changes in some Arctic and Antarctic ecosystems;
- in many glacier- and snow-fed rivers, increased run-off and earlier peak flows;
- effects on thermal structure and water quality in lakes and rivers showing warming;
- earlier timing of spring events, such as leaf-unfolding, bird migration and egg-laying;
- earlier “greening” of vegetation and longer growing seasons;
- poleward and upward shifts in ranges in plant and animal species;
- in oceans and freshwater systems, changes in algae, plankton and fish abundance;
- changes in ranges and timing of migrations of fish in rivers; and
- effects on human systems are difficult to discern due to adaptation and non-climatic influences.

Impacts will depend on changes in temperature as well as precipitation, sea levels and ocean circulation, and concentrations of carbon dioxide, as well as other features of the climate. The ability to adapt to climate change, to reduce vulnerability, is expected to be more constrained for low-income populations, especially in developing countries.

By mid-century, average annual river runoff and water availability are projected to increase by 10-40% at high latitudes and some wet tropical areas, while decreasing by 10-30% over some dry regions at mid-latitudes and in the dry tropics, some of which are already water-stressed. Drought extent, heavy precipitation events, and flood risks are expected to increase.

The resilience of many ecosystems is likely to be exceeded by an unprecedented combination of climate change, associated disturbances (e.g., flooding, drought, wildfire, insects, ocean acidification), and other changes (e.g. land use change, pollution, over-exploitation of resources).

Crop productivity is projected to increase at mid- to high latitudes for local mean

temperatures up to 1-3°C (1.8-5.4°F) and then decline beyond that in some regions. Especially in seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increases. Adaptations allow yields to be maintained for modest warming.

Coasts are projected to be exposed to increasing risks due to sea level rise, coastal erosion, human-induced pressures, more frequent bleaching of corals, loss of wetlands, and increased flooding.

Climate change may affect the health status of millions of people through increases in malnutrition, increased deaths, disease and injury due to heat waves, floods, storms, fires and droughts; increased air pollution and altered distribution of some infectious diseases.

For agriculture, most models project overall benefits over the next few decades, largely due to increased fertilization by CO₂ in the atmosphere, although negative impacts might occur in some regions and for some sub-populations.⁹⁰ As climate change progresses — several models suggest turning points at 2 to 4°C warmer than 1990 — projected impacts on crop agriculture become negative in most regions except for the high latitudes. Adverse impacts on Africa may be of particular concern.⁹¹ Research to date on agricultural impacts cannot be considered conclusive. Few studies of agriculture have incorporated the effects of climate variability,⁹² or the spread of pests, crop diseases, and weedy plants that could be favored by warmer temperatures and higher CO₂ concentrations. Very little research has been applied to other important food sources, such as fruits and vegetables, livestock production, fisheries, and crops grown to produce oil, which constitute the fastest growing shares of agriculture. Biotechnological products and cropping flexibility have only partially been included in agricultural impact studies. Experts believe impacts will also depend on migration of agricultural production to regions favored by climate change, with implications for land values and shifts in labor forces.

Climate change and the fertilization of vegetation by higher levels of CO₂ in the atmosphere are projected to have both positive and negative effects on forests. However, as species reach their higher temperature tolerances, stress and susceptibility to disease, pests, and drought are likely, possibly resulting in die-offs such as those currently being experienced by forests in parts of the western United States and Canada.⁹³ If forests and vegetation are able to migrate or expand in

⁹⁰ Robert Mendelsohn, “Measuring Climate Impacts with Cross Sectional Analysis,” *Climatic Change* (forthcoming).

⁹¹ Gunther Fischer, Mahendra Shah, and Harij van Velthuisen, “*Climate Change and Agricultural Vulnerability*,” International Institute for Applied Systems Analysis (2002), [<http://www.iiasa.ac.at/Research/LUC/JB-Report.pdf>]; M. Parry, C. Rosenzweig, and M. Livermore, “Climate Change, global food supply and risk of hunger,” *Phil. Trans. Royal Soc. B* 360 (2005), pp. 2125-2138.

⁹² Robert Mendelsohn, op.cit.

⁹³ Pacific Northwest Research Station, Western Forests, Fire Risk, and Climate Change (continued...)

conjunction with projected climate change, the composition of land cover would likely be altered, with significant agricultural, economic, cultural, and ecological consequences.

One risk appearing in some climate model projections is the possibility of dieback of the Amazon rainforest, resulting in a self-reinforcing cycle of greater drying and further dieback. This could result in an amplification of greenhouse-gas induced climate change, as well as ecological change.

Models show a wide range in the projected decrease of Arctic sea ice extent, from very little to, as most models show, an ice-free Arctic in summers by the end of the century or sooner.⁹⁴ Arctic sea ice melting is consequential for the global climate. It would have ecological effects on polar bears, seals, bird populations, and marine life, as well as on humans, including native cultural and subsistence systems, and might raise national security and sovereignty issues.

Recent research on the melting of ice sheets and accumulation of snow and ice at higher elevations of ice sheets has reduced scientists' confidence in related projections and implications for sea level rise over several centuries. While most global models project somewhat lower rises in sea levels with future warming, some scientists assert that these results contradict recent evidence in some locations of faster melting than predicted.⁹⁵ Understanding of dynamics of ice sheets is weak and a source of large uncertainty regarding future sea level rise.

Major declines of live coral cover for reef systems around the world are expected by many scientists, because of combined effects of greater frequency of high temperatures and to higher ocean acidity from elevated CO₂ concentrations. (See "Carbon Dioxide and Ocean Acidification" below.) To the degree that live coral reef cover declines, losses up the related food chain could be expected, with

⁹³ (...continued)

(2004), at [<http://www.fs.fed.us/pnw/pubs/science-update-6.pdf>]; Dale, V.H.; Joyce, L.A.; McNulty, S.; Neilson, R.P.; Ayres, M.P.; Flannigan, M.D.; Hanson, P.J.; Irland, L.C.; Lugo, A.E.; Peterson, C.J.; Simberloff, D.; Swanson, F.J.; Stocks, B.J.; Wotton, B.M., "Climate change and forest disturbances" *Bioscience*, 51, pp. 723-734 (2001); see also Flannigan, M.D.; Bergeron, Y.; Engelmark, O.; Wotton, B.M., "Future wildfire in circumboreal forests in relation to global warming" *J. Veg. Sci.*, 9 (1998), pp. 469-476.

⁹⁴ X. Zhang and J.E. Walsh, "Toward a seasonally ice-covered Arctic Ocean: Scenarios from the IPCC AR4 model simulations," *Journal of Climate* 19 (2006), pp. 1730-1747; O M Johannessen and M W Miles, "Arctic sea ice and climate change — will the ice disappear in this century?" *Science progress* 83 (Pt 3) (2000), pp. 209-22; Marika Holland, Cecilia M. Bitz, and Bruno Tremblay, "Future abrupt reductions in the summer Arctic sea ice," *Geophysical Research Letters*, 33, no. L23503 (2006).

⁹⁵ Jonathan T. Overpeck et al., "Paleoclimatic Evidence for Future Ice-Sheet Instability and Rapid Sea-Level Rise" *Science*, 311 (5768), pp. 1747-1750 (March 24, 2006); M. T. McCulloch, T. Esat, *Chem. Geol.*, 169, 107 (2000). J. H. Mercer, *Nature*, 271, 321 (1978); W. G. Thompson, S. L. Goldstein, *Science*, 308, 401(2005). H. J. Zwally et al., *Science*, 297, 218 (2002); T. A. Scambos, J. A. Bohlander, C. A. Shuman, P. Skvarca, *Geophys. Res. Lett.*, 31, 10.1029/2004GL020670 (2004).

possible economic consequences for fisheries and human food security in parts of the world.

Models predict that the northern tier of the United States, Canada, and most of Europe are likely to experience more days with heavy precipitation (above 0.4 inches) by the late 21st Century.⁹⁶ Some areas would undoubtedly benefit from increases in precipitation. More of this is likely to fall as rain rather than snow, and snow is likely to melt earlier. For some areas and systems, these changes would be positive. Many scientists conclude that it is likely that there will be some increase in tropical cyclone intensity if the climate continues to warm.⁹⁷

Projected climate change is expected to have additional major repercussions for ecological systems. The specific reorganization of ecosystems, and effects on particular populations, species, landscapes, and ecosystem services to humans are beyond reliable prediction, given relatively little monitoring and research and the rudimentary state of models for understanding these processes. The effects are expected to be highly localized, though some will be widespread and be linked to changes in other regions through food chains, nutrient flows, atmospheric and ocean circulations, etc. Some populations and species are likely to flourish in a more temperate and humid environment. Some will be able to adapt and/or migrate to stay within a hospitable habitat. Others will be affected by obstacles or patchiness of suitable pathways, or migration rates slower than the movement of the appropriate biome, disruptions in food chains or other critical dependencies among species, and increased competition. Many ecologists expect high rates of extinctions and loss of biological diversity if climate change projections are accurate.

Human health may benefit or suffer with future climate change. It is uncertain at what point increased heat stress impacts may outweigh the declining cold stress benefits;⁹⁸ that turning point will be sooner the faster temperatures rise and the slower effective prevention and response adaptations are established. Other adverse health impacts that may increase include incidence of food- and vector-borne diseases.⁹⁹ Warmer temperatures may increase air pollution, as well as boost growth of fungi, mold, and other allergens.¹⁰⁰ In terms of mortality, the potential expansion of malaria is by far the most critical health impact studied, though its growth may be

⁹⁶ Claudia Tebaldi, Katharine Hayhoe, Julie M. Arblaster, and Gerald A. Meehl "Going to the Extremes: An intercomparison of model-simulated historical and future changes in extreme events," *Climatic Change*, December 2006.

⁹⁷ World Meteorological Organization, *Statement on Tropical Cyclones and Climate Change*, Geneva (2006).

⁹⁸ Tol, R.S.J., "New Estimates of the Damage Costs of Climate Change, Part II: Dynamic Estimates," *Environmental and Resource Economics*, 21 (2) (2002), pp. 135-160.

⁹⁹ Populations of rodents, mosquitoes and other vectors spread disease to humans.

¹⁰⁰ Ebi, Kristie L., David M. Mills, Joel B. Smith, and Anne Grambsch, "Climate Change and Human Health Impacts in the United States: An Update on the Results of the U.S. National Assessment," *Environmental Health Perspectives*, 114, no. 9 (September 2006), pp. 1318-1324.

mitigated as incomes rise by the improvement of public health systems, environmental modifications and pesticides, and possible vaccines.

Carbon Dioxide and Ocean Acidification

Climate change research has revealed that elevated concentrations of carbon dioxide in the atmosphere are changing the chemistry of the oceans to a state not witnessed for at least 55 million years, prompting concern by many scientists about potentially large effects on the marine food chain. As the oceans absorb CO₂ from the atmosphere — a normal process in the carbon cycle that helps to lower CO₂ in the atmosphere and slow climate change — the dissolved CO₂ makes the normally alkaline seawater more acidic. One study has found that the oceans have become about 30% less alkaline since pre-industrial times.¹⁰¹ This process is popularly referred to as *ocean acidification*. The high dissolved CO₂ decreases *carbonate ions*, which are needed by shell-forming creatures to make *calcium carbonate* for their shells.

Research on more than a dozen species of corals and plankton indicates that net *calcification* (the process of shell-building) would decrease by -4% to -56% if CO₂ atmospheric concentrations were to double from pre-industrial levels (around 550 ppm),¹⁰² forecast by some models to occur as early as mid-century. Above varying thresholds, the decrease in growth turns to dissolving of their shells. Some species that show small effects may indicate unusual adaptive responses that may not be needed at lower CO₂ concentrations. In some cases, resource managers may be able to help protect species in some locations. However, the few forecasts available suggest potentially large impacts on the ability of coral reefs to grow under future conditions. Moreover, scientists believe the current acidification is essentially irreversible on human-time scales, as the natural processes to raise alkalinity operate far too slowly to reverse the current trend.

The main unknown in how rapidly ocean acidification will occur is the future trajectory of CO₂ concentrations in the atmosphere, which depends largely on future human-related emissions of CO₂, mostly from fossil-fuel burning.¹⁰³ Concerns for impacts are particularly great for areas where the form of carbon needed for shelling building (*aragonite*) is already low (i.e., the high latitudes) or where the ecosystems are dominated by shell-building organisms; in the case of the Southern Ocean encircling Antarctica, both conditions occur.

¹⁰¹ James C. Orr et al., “Anthropogenic Ocean Acidification over the Twenty-First Century and its Impact on Calcifying Organisms,” *Nature*, 437 (September 29, 2005), pp. 681-686.

¹⁰² J.A. Kleypas et al., “Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research,” a report of a workshop held April 18-20, 2006, in St. Petersburg, FL, at [http://www.ucar.edu/communications/Final_acidification.pdf] (accessed January 23, 2007).

¹⁰³ Orr, op. cit.

Implications of Climate Change for the Federal Government

The prospects of a changing climate have a variety of implications for the U.S. federal government. First, scientific attention and public questions about climate change have increased pressure for research to provide answers, and for elected officials to make decisions about whether and how to address climate change. The U.S. government invests around \$6 billion yearly on climate change research,¹⁰⁴ voluntary programs, and financial incentives to advance low-GHG-emitting technologies. Setting clear and realistic objectives for research and programs remain a near-term challenge for federal programs, but such measures facilitate continuing oversight of program performance and improvements. Of particular interest may be questions about the rate at which science (also integrated with economics) can narrow uncertainties about the magnitude, rate, geographic distribution, and other characteristics of climate change, and the degree to which changes may be predictable, hence facilitating effective and timely adaptation. These questions bear importantly on the trade-off between acting sooner with imperfect information versus delaying action in expectation of reducing uncertainties.

Second, the federal government manages many assets that are potentially affected by climate change. For example, climate change could bring benefits or threats to public lands, particularly to national parks and other physical and biological assets valued for their high natural and cultural amenities. As climate change alters grasslands, forests, fisheries, and other resources, their values will change, as may appropriate management objectives and plans. Similarly, climate change may affect the demand and supply of energy for the operations of government, with implications for infrastructure planning, expenses, and supply choices.

The federal government may find it desirable to redefine objectives and provide for institutional flexibility and adaptive management as climate, and the resources that depend on specific conditions, change. For example, such ecological impacts as competition among species may lead to conflicts among endangered species¹⁰⁵ or other resource management goals. Evaluations of objectives and practices in light of potential future climate change may enhance future successes of resource management.

Although some climate changes and their impacts may occur relatively smoothly, ecosystems frequently exhibit abrupt changes in response to incremental pressures. In terms of socioeconomic consequences, abrupt changes may constitute emergencies or even disasters that require federal responses and possibly financial and other resources. Preparedness for, and managing aftermaths of, hurricanes, droughts, pest infestations, fires, epidemics, coastal erosion, and deterioration of

¹⁰⁴ For more information on federal climate change budgets, see CRS Report RL33817, *Climate Change: Federal Expenditures*, by Jane A. Leggett.

¹⁰⁵ Consider, for example, competition between the Cape Sable seaside sparrow versus the snail kite, both endangered species, as drought and rainfall in the Everglades region create overlapping habitat and conflict. (Land Letter, *ENDANGERED SPECIES: As habitats shrink, conflicts between protections grow*, November 16, 2006, at [<http://www.eenews.net/Landletter/2006/11/16/#1>], extracted November 28, 2006.

permafrost are a few examples of the physical pressures climate change may bring. Such changes can also create social dislocations and strife. The Dust Bowl of the 1930s, as an illustration of a regional environmental disaster, resulted in one of the largest dislocations in U.S. history.

Beyond immediate responses, the federal government also frequently acts as the insurer of the last resort; this role could expand if private insurance becomes less available or more costly, or if people do not procure adequate insurance. The dramatic increase in economic losses since 1980 resulting from extreme weather events makes clear that economic exposures to extreme weather events, such as droughts, floods, hurricanes, tornadoes, and others can run in the billions in the United States, and much higher globally.

Many experts suggest that all levels of government may find it useful to consider possible climate change implications when planning their long-lasting infrastructure or other projects, including energy procurement, water supply and flood control, investment in buildings and transportation systems, etc. This could lessen the problem of obsolete, expensive, or *stranded* assets that could arise with possible climate and policy changes.

Further, expected climate changes outside the borders of the United States could have important implications for the U.S. federal government as well. For example, climate change impacts in Mexico, and many other developing countries, could be more adverse than in the United States, due partly to more severe projected climate changes and partly to lower capacity to adapt. The differential between United States and foreign direct impacts may increase pressure on migration and terms of trade; it may also increase demands for disaster relief, development assistance, and other types of interventions.

Implications for Policy

The federal government and other institutions have invested billions of dollars in researching climate change over more than five decades. Human emissions of greenhouse gases have increased exponentially since the Industrial Revolution, leading to higher concentrations of carbon dioxide, methane, and other gases than have existed for hundreds of thousands (maybe millions) of years. Measurements demonstrate with increasing confidence that the Earth's climate has been warming, especially in the past few decades, and changing in other ways. Science cannot explain the recent patterns of climate change without including the influence of elevated greenhouse gas concentrations. Although many uncertainties remain concerning the future magnitude, rate, and other details of climate change, a preponderance of scientists conclude that greenhouse gases emitted by fossil fuel use and other human activities are virtually certain to induce global average warming by at least 1.8°C (3.2°F) over the 21st Century — or as high as 4°C (5.2°F), and possibly more than 6°C (more than 9°F). These scientists assert that some warming is virtually inevitable, because of the accumulation of past emissions in elevated atmospheric concentrations of GHG. The time lags inherent in the climate system are an important

aspect affecting the effectiveness of various policy options. (See “Time Lags in the Climate System” below).

Time Lags in the Climate System

Timing of changes: There are long time lags between emissions of most greenhouse gases, their accumulation as rising concentrations in the atmosphere, and the induced climate change that may last from decades to millenia. Atmospheric lifetimes differ greatly among GHG — from minutes to tens of thousands of years, with CO₂ typically assumed to have half remaining in the atmosphere after about 100 years. The long-lived gases continue to influence the climate as long as they remain in the atmosphere. Thus, emissions of, say, CO₂ today are expected to continue to affect climate for hundreds of years. Conversely, slowing the growth of concentrations, or stabilizing them, would require proportionately large cuts in emissions or enhancements of removals (e.g., through uptake by trees). Dominant influence over the next 50 years is likely the accumulation in the atmosphere of past GHG emissions; changes in climate would continue for many decades to centuries after GHG concentrations cease to grow. Several points made by climate experts are important:

- Most GHG emitted today will affect the climate system for decades to hundreds of years from now.
- Reducing some gases with short atmospheric lifetimes may achieve relatively quick effects on climate, while the effects of reducing long-lived gases will have greatest effect over decades to centuries (i.e., long-term climate change).
- Near term benefits may be small for avoiding climate impacts through GHG reductions, though the benefits may be large when aggregated over the atmospheric lifetime of the gas.
- The more concentrations increase, the greater the emission reductions required to achieve any specified GHG concentration target.
- At some point, the more warming occurs, the less effective natural removals may be, requiring proportionately more GHG reductions to achieve any specified GHG concentration target.

These conclusions raise a number of questions that may help direct further research or science to support public policy decisions:

- What do policy-makers need to know from climate science in order to decide whether to address climate change further?

- Are research priorities aligned with needs, and are realistic objectives and timetables established, to answer key questions of prospective decision-makers?
- Are appropriate mechanisms in place for communication between researchers and decision-makers of many types? Considering the risks and possible consequences of decision options, how much confidence in the science (or specific conclusions) do decision-makers need in order to make choices? Do researchers know what decision-makers need from them?
- What are realistic estimates from researchers of when critically needed information can be provided at the desired level of confidence? Are decision-makers' expectations consistent with the time necessary for rigorous research and assessment?
- Since all uncertainties cannot be eliminated, are appropriate, useful risk decision tools and management regimes in place (or planned) to facilitate use of the best scientific information for different types of decisions (e.g., resource management, GHG control policies, financial decisions)?
- Is there a process to incorporate learning over time, as well as legal and institutional adjustments, to adapt to emerging scientific information?
- Do communication channels exist to ensure that relevant decision-makers (in Congress, agencies, states, localities, businesses, and households) have access to useful and reliable information to make appropriate and timely decisions?
- Are effective cooperative mechanisms (inter-governmentally and internationally) useful and in place to gain efficiencies and share insights, and yield results that are compatible with national goals?

Current and emerging science also provides key information for policy-makers that may help to resolve the details of specific decisions, such as:

- Is it timely to act now? Over what timeframe should actions be taken?
- What are the options for action and their relative effectiveness, including consideration of
 - scope of greenhouse gases or other forcing agents to cover;
 - benefits and costs of investing to learn more, or acting now, or both;
 - mechanisms to monitor achievements and refine strategies, etc.?

- What is the appropriate balance between research, acting on current knowledge, adapting to anticipated change, and informing decision-makers (public and private) of choices and implications?

There are a number of bills before the 110th Congress proposing a diversity of approaches to address climate change and greenhouse gas reductions. There also likely will be more hearings, both legislative and oversight. Thus, assuring that the best scientific underpinning is available for policy-related deliberations will remain a priority.

Appendix A: Natural Forces that Influence Climate

The Earth's climate is variable, and scientists understand, to varying degrees, the forces that have driven climate changes of the past. Many factors contribute to changes in climate, regionally and globally, and no single factor acts alone.¹⁰⁶ The principal natural factors determining climate through geologic time include the Earth's orbit around the Sun, solar activity, ocean variability, volcanoes, release of methane clathrates from the ocean bed, and *chaotic* variability. Human activities have grown to a scale especially over the past century that it is almost certain that these human activities have contributed to the climate change observed in recent decades. This appendix provides brief information on the principal identified natural drivers of climate. The human activities affecting climate — the principal reason demanding current policy attention — are described in the “Human Activities that Influence Climate Change” section above.

Earth's Orbit Around the Sun

The shape of the Earth's orbit around the Sun is not perfectly round. The Earth's axis is tilted, and wobbles as it turns. These and other other orbital behaviors are fairly well understood and predictable in the ways they influence the Earth's climate. Generally, when the Earth is closer to the Sun, the Earth receives more incoming radiation and warms.

Solar Activity

Several aspects of solar activity have been suggested as contributors to climate change, although they remain disputed: total solar *irradiance*, the *ultraviolet* component of irradiance, *cosmic rays*, and *earth/solar magnetism*. Although the validity and magnitude of these remain in dispute, cosmic rays and earth/solar magnetism remain particularly complex and poorly understood.

The variability of the Sun's *total irradiance*, or how much solar energy the Sun emits toward the Earth, influences the Earth's climate, although its significance is disputed. On long time scales, solar variability could have a large influence, as on the cold temperatures of the *Little Ice Age*,¹⁰⁷ but quantification of the solar role in climate variability over periods of centuries to millenia is poor. For example, while some scientists have found evidence that the Sun's activity may have been relatively high during the Medieval Warm Period, other scientists have found no evidence that estimated variability of Sun's total irradiance has been sufficient to drive climate variations over the past 1,000 years. For example, one study of recent climate, using a very simple model, found that solar variability may have accounted for approximately 40% of climatic variability over the past 140 years, in addition to internal (unexplained) variability, greenhouse gas forcing, and other geophysical

¹⁰⁶ S. Fred Singer, “Human Contribution to Climate Change Remains Questionable,” *EOS Transactions*, 80 (April 20, 1999), pp. 183-187.

¹⁰⁷ J. Beer, W. Mende, and R. Stellmacher, “The role of the sun in climate forcing,” *Quaternary Science Reviews*, 19 (2000), pp. 403-415.

factors.¹⁰⁸ Satellite measurements from 1978 dramatically improved the measurement of solar activity; while there is a clear correlation between solar sunspots and an 11-year radiation cycle, some scientists conclude that variations in solar output have been too small since 1978 to have significantly induced the observed global warming of the past three decades.¹⁰⁹

Solar output of *ultraviolet light* has been postulated as causing the Maunder Minimum (around 1650 to 1710) of the Northern Hemisphere's Little Ice Age, when scientists believe that the Sun was relatively quiet and emitted less ultraviolet light. This, in turn, may have reduced the ozone in the Stratosphere. Ozone is a greenhouse gas that warms the Earth, so the reduction of ozone in the stratosphere due to less ultraviolet light may have cooled the Northern Hemisphere on average by a few tenths of a degree centigrade. Some scientists have found that estimated ultraviolet variance since 1915 correlates poorly with global average temperature.¹¹⁰

Ocean Variability

At least one scientist¹¹¹ has hypothesized that the natural dynamics of ocean systems may be periodic and have an influence at least on regional or hemispheric climates. Understanding of the oceans may also elucidate factors that can trigger abrupt climate changes. For example, evidence exists that periods of increased freshwater flow to the North Atlantic and Arctic Oceans from the Laurentide ice sheet (over Canada) may be responsible for abrupt and significant climate events in NW Europe that took place in the Late-glacial and early Holocene.

Volcanic Eruptions

The presence of certain *aerosols*, or tiny particles suspended in the atmosphere, can reflect sunlight away from the Earth. Over geologic time, and in certain recent eruptions, the aerosols jetted into the atmosphere have caused significant cooling for one to several years after an eruption. About 71,000 years ago, an eruption of Mt. Toga in present-day Indonesia thrust about 2,800 times as much aerosol dust into the atmosphere as the Mt. St. Helens eruption of 1980, and may have been sufficient to cause a six-year *volcanic winter* and instigate a 1,000-year ice

¹⁰⁸ J. Beer, W. Mende, and R. Stellmacher, "The role of the sun in climate forcing," *Quaternary Science Reviews*, 19 (2000), pp. 403-415.

¹⁰⁹ P. Foukal et al., "Variations in solar luminosity and their effect on the Earth's climate," *Nature*, 443 (September 14, 2006), pp. 161-166.

¹¹⁰ P. Foukal et al., "Variations in solar luminosity and their effect on the Earth's climate," *Nature*, 443 (September 14, 2006), pp. 161-166.

¹¹¹ W. S. Broecker, S. Sutherland, T.-H. Peng, *Science* 286, 1132 (1999); Ray Bradley, "1000 Years of Climate Change," *Science* 288, no. 5470 (May 26, 2000), pp. 1353-1355.

age.¹¹² More recently, in 1992, the eruption of Mt. Pinatubo was sufficient to lower global average temperatures significantly for a few years.¹¹³

Release of Methane Clathrates from Ocean Beds

Methane is a potent greenhouse gas. Methane clathrates (or methane hydrates) are a form of ice with methane trapped in their crystalline structures that exist at cold temperatures and high pressures on the Earth's ocean floor and in Arctic continental shelves (the latter of which may be very shallow or even above ground). Some hypothesize that the sudden release of methane clathrates may have been implicated in the Earth's most severe extinction event, which occurred suddenly about 252 million years ago, resulting in a 5°C temperature increase globally, and with an estimated loss of about 96% of marine species and 70% of terrestrial vertebrate species. Another rapid warming, thought by some to have been caused by massive releases of methane clathrates or carbon dioxide, and accompanied by major extinctions, occurred at the beginning of the *Paleocene-Eocene Thermal Maximum* or the *Initial Eocene Thermal Maximum*. Sea surface temperatures rose between 5° and 8°C, and in the high Arctic, sea surface temperatures rose to about 23°C/73°F. (Today's mean annual temperature at the North Pole is around -20°C/-4°F.) There is corroborating evidence in a rapid color change of ocean sediments that normal deposition of white calcite shells of ocean animals stopped for some 50 thousand years, which may have occurred with accompanying ocean acidification.¹¹⁴ (See "Carbon Dioxide and Ocean Acidification" above.)

Water Vapor

Water vapor exists naturally in the Earth's atmosphere and is the most important greenhouse gas (see "Greenhouse Gases" section), accounting for around two-thirds of the 33°C of additional warming our planet receives because of the presence of its atmosphere.¹¹⁵ However, a change in water vapor content of the atmosphere can have warming or cooling effects, depending on where it is in the atmosphere, in latitude and altitude. Warmer temperatures globally will tend to increase the water vapor in the atmosphere, a *positive feedback* that tends to amplify the warming. To the degree that certain clouds increase, especially low clouds, with increased water vapor, a *negative feedback* may result, reducing the warming. Much of the warming predicted by climate models in response to GHG results from amplification by increased water vapor in the atmosphere from the initial increase in GHG-forced temperature. Feedbacks to clouds are among the least understood processes and account for large differences among climate model results. Although

¹¹² NOAA at [<http://www.ngdc.noaa.gov/paleo/ctl/clihis100k.html#>].

¹¹³ D Santer et al., "Contributions of anthropogenic and natural forcing to recent tropopause height changes," *Science*, 301, no. 5632 (July 25, 2003), p. 479.

¹¹⁴ Zachos, James C., Ursula Rohl, Stephen A. Schellenberg, Appy Sluijs, David A. Hodell, Daniel C. Kelly, et al. "Rapid Acidification of the Ocean During the Paleocene-Eocene Thermal Maximum," *Science*, 308, no. 5728 (June 10, 2005), pp. 1611-1615.

¹¹⁵ Lee R. Kump, "Reducing uncertainty about carbon dioxide as a climate driver," *Nature*, 418 (September 12, 2002), pp. 188-190.

significant scientific advances in understanding clouds have been made since the year 2000, it will be at least several years before these are fully incorporated into scientific assessments, and no doubt considerable uncertainty will remain for decades.

Chaotic Variability

Climate scientists say that there is natural or “chaotic” variability in the climate system, meaning that there is a certain amount of random or unexplained behavior of the climate. To some degree, this natural variability reflects what science has not identified, cannot explain, or does not find a regular statistical pattern to describe. The presence of unexplained variability does not mean that scientists cannot make meaningful and useful statements about the past or future; it means that there is an amount of uncertainty, resulting from unidentified or poorly understood factors or randomness, that will remain in forecasts of the future.